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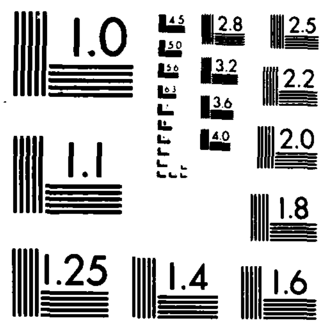
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VEHICULAR SIMULATION-INDUCED SICKNESS, VOLUME I: AN OVERVIEW

by

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Simulator-induced sickness is a serious problem which ~~afflicts~~ is provided the users of certain unprogrammed vehicular simulators, including aircraft and driving devices. This report provides background information on the sickness problem, a discussion of its parameters, implications in training and research applications, and theoretical underpinnings. The majority of the report comprises a literature review specific to simulator sickness. All available articles, reports, technical memoranda, and papers directly dealing with the problem of operator discomfort in vehicular simulators were obtained and reviewed. These included a number of incidence reports, investigations of inter- and intra- individual differences with respect to susceptibility, and laboratory and field experiments on simulator sickness. Drawing from the literature review, the report provides an overview of the major etiological factors of simulator sickness. ~~Finally~~, a number of potential countermeasures for reducing or eliminating the problem are presented. For quick-reference, a tabular summary of simulator sickness studies and accounts is also included in an appendix.

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SUMMARY

Simulator-induced sickness is a serious problem which afflicts the users of certain unprogrammed vehicular simulators, including aircraft and driving devices. This report provides background information on the sickness problem, a discussion of its parameters, implications in training and research applications, and theoretical underpinnings. The majority of the report comprises a literature review specific to simulator sickness. All available articles, reports, technical memoranda, and papers directly dealing with the problem of operator discomfort in vehicular simulators were obtained and reviewed. These included a number of incidence reports, investigations of inter- and intra-individual differences with respect to susceptibility, and laboratory and field experiments on simulator sickness. Drawing from the literature review, the report provides an overview of the major etiological factors of simulator sickness. Finally, a number of potential countermeasures for reducing or eliminating the problem are presented. For quick-reference, a tabular summary of simulator sickness studies and specific simulator designs are included in an appendix.

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ORGANIZATION OF THE REPORT

This report constitutes an overview of the literature directly dealing with simulator sickness in flight and driving devices. The report is organized into seven major chapters. A brief description of the information included in each chapter follows.

Chapter I. Introduction

This chapter discusses the incidence of simulator sickness in various devices and the range of its manifestations in simulator operators. Also, the problems arising from the occurrence of simulator sickness are explained, with respect to their effects on training and research efforts.

Chapter II. Theoretical Underpinnings

Relationships between "simulator sickness" and "motion sickness" are considered, along with a brief discussion of perceptual conflict theory as it addresses simulator sickness.

Chapters III through V. Chronological Literature Review

Given the necessary background in Chapters I and II, Chapter III moves into the actual literature review documentation of simulator-induced sickness. Approximately 65 references directly pertinent to simulator sickness were included in a selected annotated bibliography (Volume II of this report, Casali and Roesch, 1986) and are reviewed herein. Of course, the body of literature dealing with motion sickness is quite vast, and motion sickness research per se was not the aim of this review, save for the subset dealing specifically with simulator sickness. The reader specifically interested in motion sickness is referred to the excellent reviews by Benson (1978), Kennedy and Frank (1983), Money (1970), and Reason and Brand (1975).

The objective of the literature review is to compile and integrate all available data specifically dealing with simulator sickness, its theoretical underpinnings, potential causes, symptomatology and suggested countermeasures. It is hoped that the review will be beneficial to those undertaking research on simulator sickness, to simulator designers working on new devices, and to simulator users needing to institute measures to minimize the occurrence of sickness with devices currently in operation. Some of the documents surveyed may not be readily accessible as they do not appear in the open literature but exist only as technical correspondence or isolated research reports. These are reviewed in some detail. Other documents are drawn from a variety of human engineering, aerospace medicine, and experimental psychology journals and texts.

The literature is discussed in chronological order under three major chapter headings. Chapter III, Incidence Reports, cites reports and memoranda with mention of incidental and anecdotal evidence of sickness in specific simulators. Most of these reports are not research-oriented but do contain information on the incidence rates and extent of the sickness problem.

Chapter IV, Research on Individual Differences, reviews research literature aimed at investigating individuals' susceptibilities to simulator-induced sickness. In particular, research on perceptual style (field-independence/dependence) has been fairly extensive and is covered in considerable detail.

Chapter V, Experimentation Reports, concentrates on those laboratory or field studies directly investigating simulator design and procedural (usage) aspects influencing sickness. This body of literature differs from the anecdotal reports reviewed in Chapter III in that the primary aim (of the various research studies) was to assess simulator sickness using at least some degree of controlled manipulation and experimental measurement.

Chapters III-V are augmented by a tabular overview of each cited report or research study on simulator sickness in the Appendix. This set of tables organizes each study by author(s) and includes an extensive coverage of the task scenario used, subjects, independent variables, dependent measures, and major results. Incidence and anecdotal reports are also summarized in the tables. Furthermore, for those desiring a full description of each simulator cited in the text of this report, a table of flight and driving simulator characteristics, organized by device, is provided in the Appendix.

Chapter VI. ͵tential Design Etiological Factors

Drawing upon the literature review in Chapters III-V, an overview of suspect design aspects which appear to have potential for influencing simulator sickness are elucidated in Chapter VI. These factors are grouped under control loop temporal characteristics (e.g., lags and delays), dynamic inaccuracies, control loading, proprioceptive-cuing motion system characteristics, visual display issues, cockpit environment issues, and interactive effects. Many of these simulator design characteristics are amenable to research inquiry and are discussed in this light.

Chapers VII. Procedural Countermeasures

This final chapter provides recommendations for reducing the incidence of simulator sickness via procedural countermeasures. These procedural suggestions are simply that; they do not require any hardware retrofit of the simulator. It should be noted that merely altering the operational procedures cannot be expected to circumvent the simulator sickness problem in a device with inherent design problems which provide etiological stimulation.

I. INTRODUCTION

Background

In the past two decades there has been considerable effort aimed at the improvement of simulator technology and the enhancement of fidelity in simulators used for training and for research. However, the utilization of a number of vehicular simulators, namely aircraft and driving devices, has been hindered by a problem termed "simulator sickness, simulator aftereffects, or simulator syndrome." Simulator sickness is used to identify the constellation of symptoms which may be experienced by humans as a result of flying or driving a simulator. It may be manifested as an acute symptomatology during the simulator experience, including such problems as disorientation, dizziness, headache, pallor, burping, nausea, emesis, and degraded vehicular control and task performance, or as residual effects such as prolonged nausea, fatigue, motor dyskinesia, visual dysfunctioning, and ataxia lasting for up to several hours post-exposure (Casali, 1981; Frank, Kellogg, Kennedy, and McCauley, 1983). Furthermore, delayed simulator aftereffects have been experienced by simulator aircrews as late as ten hours after simulated flight (Kellogg, Castore, and Coward, 1980). Aftereffects may include the aforementioned symptoms in addition to sudden, compelling flashbacks to the simulator experience, disorientation, spinning sensations, visual illusions, and loss of equilibrium.

Simulator sickness has been recognized as a problem since the late 1950's, when it first was observed in flight trainees in a helicopter simulator (Havron and Butler, 1957). However, it has since received only a limited amount of research attention, perhaps largely because it is a difficult problem to study. The majority of the associated literature presents anecdotal and incidental evidence attesting to the magnitude of the simulator sickness problem. Relatively few research studies resulting in data and design recommendations have been conducted. However, it is largely agreed upon in the vehicular simulation community that the sickness problem is frequent and severe enough to warrant serious concern. It must be reckoned with both in the design of future simulators and in the operation of existing devices to minimize its occurrence. This is perhaps best and most recently evidenced by the collective request from the Naval Training Equipment Center (now Naval Training Systems Center), the Army Research Institute, and the Air Force School of Aerospace Medicine to assemble vision and vestibular research scientists, simulator designers, and simulator users at a 1983 National Research Council Workshop on Simulation Sickness. This is the first known formal gathering aimed at the simulator sickness problem (McCauley, 1984). From the results discussed in the Proceedings of this workshop, combined with other recent pioneering efforts aimed at the controlled study of simulator design influences on simulator sickness (e.g., Crosby and Kennedy, 1982; Frank et al., 1983; Kennedy, Dutton, Ricard, and Frank, 1984; Puig, 1984), it appears that significant interest in the simulator sickness problem has rekindled and it has become an important topic for scientific research.

Implications of Simulator Sickness

Simulators have proven useful in a variety of applications, including research and design, training, screening, and proficiency maintenance. In each of these applications, the presence of simulator sickness may pose one or more of the following problems (Casali, 1981; Frank et al., 1983; McCauley, 1984).

1. Inappropriate behaviors. The fact that subjects may experience

sickness in a simulator but not in the actual vehicle it is designed to replicate is an indication that the sickness is inappropriate. For instance, drivers of automobiles rarely get sick but passengers often do (Tyler and Bard, 1949). However, in the simulator the opposite often occurs. That is, certain driving simulators are known to induce sickness in the driver, which is a spurious result. If it were the case that simulator subjects experienced sickness in the simulator under precisely the same conditions and task scenarios for which they experienced motion sickness in the actual system, then the simulator-induced sickness would theoretically be appropriate and even desirable from a validity standpoint. However, since the simulator produces sickness which appears to be etiologically dissimilar from that encountered in the actual system, then there is evidence that the simulation is inadequate (Frank et al., 1983).

2. Threat to validity. The presence of simulator sickness constitutes an extraneous source of variance which does not correspond to responses observed in the actual system. Therefore, simulator-induced sickness poses a severe threat to the validity of the simulation and consequently to the generalizability of the resultant simulator data to the actual system or transfer task. If the validity of the device is suspect, little credence may be placed on the human operator response data from the simulation.

3. Compromised training. As noted by Frank et al. (1983) and McCauley (1984), trainees may be distracted and lose their motivation toward training objectives if they undergo discomfort in the simulator. Trainees may also ingrain certain strategies that they adopt in the simulator for alleviating sickness, such as avoiding using certain cockpit windows where display distortion may be evident, which may be totally unacceptable in the actual

aircraft. Furthermore, trainees may develop incorrect expectancies and acquire inappropriate responses in the simulator which may result in habit interference and even perhaps negative transfer when they later perform in the vehicle. This wastes both instructor and trainee time as well as simulator and operational vehicle time.

4. Reduced simulator utilization. If instructors and trainees experience discomfort in the simulator it is less likely that they will be apt to place confidence in their simulator training and consequently may not use the simulator in a serious and/or consistent manner (Frank et al., 1983). Furthermore, if "word gets around" among trainees, instructors, or researchers that a simulator has a history of inducing sickness, simulator utilization is inhibited and resulting data may be questioned as to their validity. This phenomenon may have a snowball effect, reducing the considerable usage potential of vehicular simulators.

5. On-ground risk. The potential for post-simulator aftereffects contributing to trainee/subject safety hazards is apparent but not well-documented. For instance, disequilibrium following simulated flight may place the trainee at risk when exiting a two-story simulator cab by gantry and ladder (Frank et al., 1983). Furthermore, this author has spoken with two pilot trainees who experienced post-simulator spinning sensations and visual dysfunctioning during their drive home after a simulator flight. In both cases, the trainees were compelled to stop their cars and recover from the flashback experience.

6. In-flight risk. As noted by McCauley (1984), there exists no hard evidence that in-flight accident probability can be correlated with simulator aftereffects. However, the potential certainly exists. In fact, some simulator users have recommended that actual flight be postponed for up to 12

hours after simulated flight (e.g., FITRON 124, 1981), and some British flight instructors have related that trainees are more likely to become disoriented in flight after a simulator hop. If a simulator does indeed result in a trainee's adaptation to a set of perceptual dynamics different from those of the actual aircraft, the learned responses could quite possibly result in severe habit interference in actual flight (McCauley, 1984).

7. Ethics. In military training efforts, the potential for simulator sickness from an ethical standpoint is probably outweighed by the necessity and benefit of the training; however, the same does not exist for most research simulators. In many simulator-based research studies, disclosing, to a subject prior to the experiment, the known potential of the device for inducing sickness may not be desirable because the subject's behavior may be biased. However, if a simulator does have a penchant for eliciting sickness, this fact should be made evident to a subject who is making a decision to participate, using accepted principles of informed consent.

II. THEORETICAL UNDERPINNINGS

Terminology: Motion Sickness versus Simulator Sickness

Motion sickness is a malady generally attributed to exposure to motion or to certain aspects of a moving environment. It is also generally accepted that stimulation of the vestibular apparatus of the inner ear is necessary for the inducement of motion sickness in humans (Money, 1970). Also, as Tyler and Bard (1949, p. 104) stated, "the primary cause of motion sickness is motion and the occasional failure to appreciate this fact has led to confusion."

If one adheres strictly to these definitions, then the term "motion sickness" cannot be used to refer, in a global sense, to sickness induced by simulators. This is best supported by the evidence that some fixed-base simulators, which provide no direct vestibular stimulation, produce sickness in their operators. Because these simulators impart no physical motion, the sickness they cause should probably not be referred to as motion sickness. Even though the symptomatology of the simulator-induced syndrome may be similar to that of motion sickness, although typically less severe, the causes may be quite different. In a moving-base simulator, some aspect of the motion cues may influence sickness but it is questionable that the motion alone is a sufficient stimulus. After considering the number and extent of visual (and other) cues that a simulator subject experiences, it becomes quite apparent that simulator sickness is polygenic and not restricted to a motion-based etiology.

One may adopt the somewhat relaxed posture that simulator sickness is a special subset of motion sickness if it is assumed that motion sickness can be used to describe physiological and psychological symptoms resulting from the <u>illusion</u> of a moving environment, as well as from an <u>actual</u> motion. In this conceptualization though, vestibular stimulation may not be requisite. By the very nature of the vehicles they replicate, simulators attempt to recreate the dynamics of the vehicular control task through combinations of changing cues via some or all of the following avenues: visual out-the-window scene, instrumentation, vestibular cuing, kinesthetic cuing, somesthetic stimulation, control feedback, and auditory cuing. Motion is a consequence of vehicular control actuation (or environmental influences) and many of these simulator feedback avenues reflect some aspect or conjunctive effect of the motion inherent in the control situation. Therefore, the simulation, whether fixed-base or not, attempts to create the illusion of a moving, dynamic environment and the sickness that results from the simulator experience likely emanates from some aspect of the illusory stimulus array. As demonstrated by Parker (1964), the visual presentation of filmed violent motion alone is sufficient to induce motion sickness symptoms. Parker reported that in the absence of vestibular stimulation, motion sickness was evidenced by increased volar skin conductance, increased facial temperature, decreased finger pulse volume and respiration rate, and increased heart rate in subjects who viewed a film depicting rapid, twisting automobile driving. Furthermore, 30% of Parker's subjects became so ill that they had to leave the experiment. This is strong evidence for the compelling effects of visually-implied motion.

Because the simulator represents an incomplete replication of stimuli inherent in a moving vehicular environment, the genesis of its sickness is likely motion-related but not restricted to true physical motion. Furthermore, sickness occurrences in a flight simulator do not necessarily match motion sickness-provocative situations in the actual aircraft. Therefore, it is the position of this author, in agreement with those previous (Barrett and Thornton, 1968b; Frank et al., 1983), that the term simulator sickness, not motion sickness, be applied to those infirmity symptoms and aftereffects associated with exposure to a simulator. Motion sickness may then be reserved for those situations (automobile, air, sea, etc.) where the eliciting stimulus comprises actual motion which mobilizes vestibular activity.

Theories of Simulator Sickness

A number of theories attempting to explain the origination of motion sickness have surfaced in the literature and are reviewed by Kennedy and Frank (1983) with respect to their plausibility for simulator sickness. Briefly these theories include: 1) vestibular overstimulation theory, which states that motion sickness is a consequence of overdriving the vestibular system (McNally and Stuart, 1942); 2) fear/anxiety theory, which suggests that motion sickness susceptibility increases as a direct function of fear/anxiety in the individual (Benson, 1978), 3) balance of autonomic activity postulate, which suggests that motion sickness symptoms may emanate from imbalance between parasympathetic and sympathetic nervous system mobilizing functions (Tang, 1970), 4) toxic reaction theory, which relies on the supposition that the body responds to motion-induced discomfort as if it were a toxin, thereby producing an emetic reaction to rid itself of the poison (Treisman, 1977), and 5) fluid shift theory, which purports that motion sickness directly results from an abnormal shift in fluid volume within the body (especially in the brain) due to motion stimulation and/or weightlessness, and causing either inadequate or or overabundant cerebral circulation (e.g., Lackner and Graybiel, 1983; Steele, 1968). The final explanatory theory on motion sickness, perceptual conflict theory (Steele 1968), is currently the most widely-accepted working model explanation for simulator sickness (Frank et al., 1983; McCauley, 1984).

Perceptual conflict theory. Also known as neural mismatch, sensory conflict, sensory rearrangement, cue conflict, and perceptual decorrelation, perceptual conflict theory postulates that motion sickness, a disorder of the central nervous system, is a reaction to discrepancies among motion information perceived by various sensory channels and also may be due to inconsistencies between expected sensory inputs and experienced sensory inputs. Basically, the theory states that sensed motion information from the vestibular, kinesthetic, and visual systems is input to a referencing framework whereby the inputs are compared with a neural bank of expectancy information based largely on past experiences or on naturally endowed system wiring (Kennedy and Frank, 1983). As noted by Kennedy, Berbaum, and Frank (1984), motion sickness may be manifested as an emetic reaction to a stimulus which results in decorrelation among receptor expectancy inputs which have been ingrained over time. This cue conflict, in the decorrelation sense, can be thought of as a discrepancy between stimuli appearance (perceived) and stimuli reality (e.g., Kennedy, 1970). In normal conditions, the perception of the stimuli coincides with the known reality of the stimuli, and the stimulus-response expectations are built up in a neural bank over time and become more salient with continuing motion experience. Conflict occurs when stimuli perceptions are not in accord with expectancies in memory store for each sensory channel, either spatially (gain), temporally (phase), or both.

Originally, the perceptual conflict theory tended to concentrate on the occurrence of lack of inter-modality correlation, such as between visual and vestibular inputs. As noted by Kennedy, Berbaum, and Frank (1984), the visual/vestibular conflict may be primarily in the spatial domain but phasing differences (e.g., in differing input delay times between channels) may also be problematic. Intra-modality decorrelations are also explicable under the perceptual conflict notion. Differing perceptions from the semicircular canals and the utricle/saccule otoliths may constitute a vestibular/vestibular conflict sufficient to elicit space sickness (e.g., Guedry, 1970). Furthermore, Leibowitz and Post (1982) report data which point to the possibility that visual/visual intra-modality conflict may occur between the focal and ambient systems. In fact, this is alluded to in an early citing of simulator sickness in a helicopter simulator, where ambient visual perception of the display scene gave the impression of forward motion while focal perception cues were largely conveying a receding depth (Miller and Goodson, 1958, as noted in Kennedy et al., 1984).

This leads to the utility of perceptual conflict theory in accounting for simulator sickness. Several examples of conflict situations warrant mention. First, in the case of the fixed-base simulator sickness problem (e.g., Barrett and Thornton, 1968b; Miller and Goodson, 1960), it has been suggested by a number of authors that a cue conflict arises when the subject visually senses the appearance of incident motion but never receives corresponding acceleration and/or positional cues. That is, the visual motion cues must be interpreted in isolation from physical motion cues (Puig, 1970, 1971). As Puig (1971) reports in his discussion of visual and motion cue interaction, the visual perception of displayed acceleration, deceleration, and/or reversal in direction of motion, and not the visual depiction of motion itself, is the critical stimulus for eliciting discomfort. The conflict arises when the vestibular and kinesthetic systems indicate no motion or no postural changes in spite of the compelling visual cues conveying otherwise. Thus, there is an inter-modality conflict between the vestibular/kinesthetic cues which signal that the person is not moving and the visual cues that indicate otherwise.

Within the perceptual conflict theory framework one may also account for the well-documented occurrence that experienced pilots and drivers are more susceptible to simulator sickness than novices (e.g., Casto, 1982; Frank et al., 1983; Havron and Butler, 1957; Reason and Diaz, 1971). The new trainee, inexperienced in flying the aircraft, has not developed a strong referencing framework of expectancies regarding the aircraft's responses to control inputs. Therefore, discrepancies in simulator motion feedback and aircraft motion feedback are not as evident to the novice and may not give rise to perceptual conflict leading to discomfort. However, the veteran or instructor pilot, highly familiar with the aircraft's control behavior, may experience cue conflict if feedback systems in the simulator are not in accord (e.g., inappropriate phasing differences between visual and motion updating), or if important cues are missing (e.g., lack of vestibular and kinesthetic sensations that the pilot has learned to interpret and use). Furthermore, cue conflict may arise in the visual system as a result of display distortion which may be more apparent to the experienced pilot than to the novice. If the simulator display is distorted, blurred, inappropriately collimated, or if cues that the display is actually much closer than optical infinity are apparent (e.g., edges of a CRT), then the visual input may be in spatial conflict with expectancies about the dynamic real scene. In this case, the distortion is likely to be more of a problem to the experienced pilot who has learned to scan the complete scene rather than concentrate on a specific portion, as the novice may do (Miller and Goodson, 1958; Puig, 1970).

Perceptual conflict may also explain the relative prevalence of discomfort experienced in simulators which have used oversized tilt (i.e., pitch and roll) cues to give the illusion of translational acceleration (i.e., longitudinal and lateral). Once used in several closed-loop driving simulators, these motion-base systems are no longer common. They have largely been replaced by synergistic, six-actuator systems or cascaded systems of other forms (e.g., Casali and Wierwille, 1980). These motion-base systems save space and cost by eliminating true translational positioning in the motion base. By tilting (rotating) the subject in the roll axis, the lateral acceleration forces of cornering and lane-changing are presented. Similarly, by rotating the subject in the pitch axis, an attempt is made to present the effects of longitudinal acceleration and braking. While the angular rotation does indeed produce a lateral or longitudinal component of acceleration to a seated subject, perceptual conflict may occur when the subject senses the salient rotational aspect of the motion, which is in this case an artifact of the simulator's behavior. Disparity may arise when the subject actually perceives the motion as rotational when the motion the subject expects is translational. In labyrinthine terms, the semicircular canals signal a change in position of the head resulting from rotation of the simulator motion base, when the expected sensation is linear acceleration as primarily transduced by the otolith organs.

A final example of simulator-induced cue disparity which fits in well with the perceptual conflict notion is that of differential discomfort levels among simulator crew members. Several reports (e.g., COMPATWINGSLANT, 1980; Miller and Goodson, 1958; Puig, 1971; Wenger, 1980) indicate that "passengers" in the simulator, such as instructor pilots, may have a higher incidence of sickness than pilots or drivers. This parallels the fact that motion sickness is rare among drivers of actual vehicles but prevalent among passengers (Tyler and Bard, 1949). Barrett and Thornton (1968b) offer an explanation within the cue conflict framework. Because the passenger receives no feedback from the vehicle controls and may not be in an optimum position for viewing the visual control part of the task, he or she may not have the necessary referents to anticipate vehicular motions. Therefore, response expectancies for the passengers may be more incongruous with actual feedback cues than those for the operator who is inside the control loop. However, in some simulators, higher incidence of sickness among passengers than operators may result from other factors. For instance, while an aircraft simulator display may be designed for pilot-only viewing, the instructors, flight engineers, copilots, etc., may be able to view the display from a distorted, off-axis position and receive a poor visual representation. Others may be seated in a position where the center of rotation and/or translation of the simulator's motion base may not be optimal for mimicking the expected motions of the actual vehicle. In these and other similar configurations, perceptual conflict theory may again be applied to explain the occurrence of sickness.

It should be noted that the perceptual conflict theory has several drawbacks in that it does not clearly predict the incidence of sickness in some well-known sickness-inducing situations (e.g., McCauley, 1984). Furthermore, it is primarily useful in an ex post facto explanatory sense rather than in a predictive sense. One example in which the theory may exhibit difficulty is in explaining the case where copilots are not as susceptible to simulator sickness as pilots in certain devices (in contrast to the prevalence of passenger over pilot sickness discussed earlier). In the Navy CH-53E moving-base helicopter simulator (device 2F121), the primary out-the-window displays are for the pilot while the copilot is largely in an Instrument Flight Rules (IFR) mode. However, both receive the same inertial cues but the pilot is much more susceptible to simulator sickness. In keeping with the cue conflict framework, the copilot would appear to have the major conflicts, i.e., lack of visual cues to correspond with physical motion cues, lack of control feedback, etc., and therefore might be expected to have more of a tendency toward discomfort. However, the absence of these cues may be insufficient for constituting a sensory conflict for the copilot, while the possible discrepancy between compelling visual and physical motion cues and/or between these cues and their real system analogues may constitute a salient conflict for the pilot, sufficient to elicit sickness.

While the perceptual conflict theory may exhibit certain deficiencies, it does offer plausible explanations for most known phenomena associated with simulator sickness. Most researchers agree that it offers the best working model framework for simulator sickness and therefore warrants further validation effort (McCauley, 1984).

In the following three chapters, a review of the literature on simulator sickness incidence citations (Chapter III), perceptual style and other individual differences research (Chapter IV), and controlled studies on simulator sickness (Chapter V) is presented.

III. INCIDENCE REPORTS

Most of the literature on simulator sickness consists of either formal documentation or anecdotal mention of subject or trainee discomfort arising with the use of a particular simulator. Usually these reports of sickness are mentioned in the context of their hindrance to the objectives of a simulator evaluation, training, or research effort and are not the focus of an empirical investigation. Published reports of this nature are surveyed in this section in chronological order under both aircraft simulator and driving simulator headings. Some reports are very scant in their documentation of the sickness problem while others offer much insight into the potential causes of sickness specific to the simulator and mention potential countermeasures to alleviate the problem. In all cases, the reports are reviewed herein to the fullest extent possible with respect to those aspects pertinent to simulator sickness.

Incidence in Aircraft Simulators

Early helicopter simulator sickness. The first known published reports of simulator sickness resulted from the problem arising in Bell HTL-4 helicopter simulator (device 2FH2) training effectiveness studies by Havron and Butler in 1957. The fixed-base, point-light source display device was designed to train pilots in hovering and other near-ground and at-altitude maneuvers. From their evaluation study using 36 student pilots, Havron and Butler found that the simulator lacked fidelity in a number of flight display-control relationships and concluded that these problems contributed to simulator sickness and negative transfer of training. Of eleven instructor pilots used in the evaluation, seven (64%) had to quit primarily due to sickness. Overall, 28 (78%) of those using the simulator experienced some infirmity symptoms. Largely based on their bouts with simulator sickness and device infidelities affecting transfer of training, Havron and Butler recommended against the 2FH2 simulator, as configured, for operational flight training.

While the Havron and Butler study did not set out to study sickness, it became such an acute problem during the evaluation process that a questionnaire was developed to ascertain its severity. Of 36 respondents, 28 (78%) indicated that they had experienced some degree of sickness including such acute symptoms as dizziness, nausea, vertigo, headache, sweating, and blurred vision. Over half reported residual symptoms and attentional difficulties persisting for greater than an hour after simulated flight, while five (14%) pilots had symptoms which continued overnight. The respondents differed somewhat with respect to their onset of sickness and adaptation to the problem, as some experienced discomfort only in the initial hops while others (especially instructors) were not sick initially but developed problems in later hops. Instructors had more frequent and extreme bouts of sickness than students. Havron and Butler alluded to the possibility that the experienced instructors' cue conflicts were more salient than the trainees', because their response expectancies were more developed and therefore, they were more sensitive to simulator-helicopter differences. Furthermore, the instructors were more passive (out of the control loop) than the trainees who actually flew the simulator.

Havron and Butler noted a number of potential simulator design factors which may have influenced the high rate of sickness. These centered around fidelity limitations of the visual scene, such as double images, blurry displayed objects, lack of ground texture, display vibration and discontinuities, inappropriately scaled (too large) pitch and roll excursions, incompatibility among displayed motions, and lack of retinal disparity (i.e., both eyes seeing the same image). Sickness was less of a problem when a high-altitude transparency was displayed instead of the low-altitude transparency. Lack of binocular disparity seemed to be less of a problem at high-altitude as did attention to ground detail. The scene detail was more complex, more apparent (close), but fuzzier in the low-altitude transparency. In their very thorough scrutiny, Havron and Butler also observed that certain vehicular control problems existed in the simulator which likely influenced discomfort as well as reduced training effectiveness. Marked (one to two seconds) lag in environmental feedback to cyclic and throttle inputs was noted along with helicopter-to-simulator control displacement discrepancies. Related to these control problems, student pilots who flew themselves into an oscillatory condition, such as pitch, roll, and hover oscillation, were most susceptible to sickness.

Interestingly, Havron and Butler also mentioned claustrophobia and the power of suggestion (from talking with other personnel) in influencing discomfort in the simulator, as well as the lack of proper inertial cues to correspond with the visual motion. Finally, in a countermeasure test with eight trainees who ingested dramamine, only one reported that the drug alleviated sickness. Of course, the drowsiness and potential ataxic/dyskinetic side effects of the drug would preclude its use in simulators used for vehicular control instruction or research.

In their 1960 article, Miller and Goodson, based on personal experiences with the 2FH2 device, offered a number of potential hypotheses for the sickness problem, most of which are related to the Havron and Butler observations. They emphasized that the cyclic control input-to-output lag, two to three times that of the actual helicopter, caused the pilot to over-control the simulator and "chase" the aircraft. Often this resulted in violent oscillations, loss of control, and sickness. The authors also observed that the complex low-altitude display, bombarding the subject with a multitude of detail, may likely have contributed to dizziness and nausea. Miller and Goodson presented a strong case for the influence of dynamic distortions in the visual scene, which changed with head and transparency movement, producing an "unrealistic elastic environment." They noted that while static distortions may have been adapted to by the pilot and therefore were tolerable, dynamic visual distortions resulting from such problems as varying parallax and changes in screen curvature were difficult to resolve.

Finally, Miller and Goodson (1960) posited that perceptual conflict arising due to the lack of inertial motion cuing was not likely conducive to simulator sickness, but that conflicts within the visual presentation were problematic. They maintained that because the motion cues of acceleration and deceleration to which humans are sensitive had nearly imperceptible levels in the actual HTL-5 helicopter, their absence would not constitute a salient conflict in the simulator. However, the authors did not discuss the known sensitivity of the vestibular system to positional changes (or to assumed non-level positions) in pitch and roll and their lack of inclusion in the simulator, which may contribute to a conflict with visually-depicted rotation.

<u>V/STOL simulator sickness</u>. In 1967, Sinacori reported that vertigo and sickness accompanied the use of a fixed-base, point-light source display experimental V/STOL simulator which displayed an image extending $\pm$ 100° in

azimuth and $\pm$ 30° in elevation. Pilot nausea was reported to be higher during hovering and altitude reversals and its incidence increased as flight duration increased. Nausea onset seemed to be coincident with control-induced oscillations during vigorous altitude reversals, as the pilot had a tendency to overcontrol in these maneuvers. Furthermore, Sinacori noted that inadvertent head movements occurred frequently during flight. Later, a pitch, roll, yaw motion base, with 12 degrees angular excursion in each movement and a bandwidth of greater than 10 Hz was added in an effort to alleviate sickness and improve the simulator's validity (Sinacori, 1983). In adjusting the washout strategy for this motion base, a short time constant (i.e., one second, nearing fixed-base performance) resulted in inappropriate control oscillations and nausea. When a time constant of two to three seconds was used, control fidelity was reported to be high and sickness was absent in student pilots; however, an infrequent "twinge" was reported by some experienced and instructor pilots. Overall, the addition of the motion base and careful adjustment of critical motion parameters appeared to largely alleviate the sickness problem in the V/STOL simulator based on a small pilot sample (12). In contrast to Miller and Goodson's prediction about the ineffectiveness of the addition of a motion base in reducing cue conflict in the helicopter simulator, it appears that the motion base largely eliminated salient conflicts in the V/STOL device, preventing sickness.

Additional countermeasures noted by Sinacori included the use of eyeshades to prevent direct light from the point-light source and surface reflections from the transparency from entering the pilot's vision, the procedure of not allowing pilots to view sudden visual motion slewing during startup, shutdown, and reset procedures, instructing pilots to scan the display rather than fixate on points, and providing frequent rest breaks.

<u>SAAC simulator sickness</u>. The current Air Force F-4 Simulator for Air-to-Air Combat (SAAC) has a considerable record of inducing simulator sickness. This complex simulator has a visual field of 300 degrees horizontal by 180 degrees vertical formed by a mosaic of eight CRTs displaying other aircraft and computer-generated background. Motion cues are presented via a six degree-of-freedom hydraulic base, g-suit, g-seat, and g-dependent display dimming. In a field study discussed in detail later, Hartman and Hatsell (1976) found that 2 (14%) of 14 test subjects experienced severe nausea in the simulator while other symptoms were reported at a much higher percentage. Two pilots were known to reach full emesis. In an informational report, Coward, Kellogg, and Castore (1979) also reported the occurrence of aftereffects associated with flying the SAAC. A few pilots related a "replay" illusion, where a flashback to visual sequences experienced earlier in a SAAC mission had suddenly pervaded their current mental activity. Other disturbances included illusory stimulation of the sense of flying while watching TV, inversion of the visual field, and prolonged imbalance and dyskinesia. Coward et al., reported that most symptoms were suppressed with repeated exposures to the SAAC. They also noted that because of peer pressure influence or fear of being grounded, some pilots may be reluctant to report symptoms.

<u>P-3C simulator sickness</u>. Of the six Navy sites employing the 2F87F OFT (operational flight trainer) the Naval Air Station (NAS) Brunswick has the most fully documented history of aircrew sickness. The 2F87F, which simulates the flight deck (three crew) of the Lockheed P-3C aircraft incorporates a synergistic six-actuator motion base and a CRT infinity optics computer-generated display system with 48 degree horizontal by 36 degree

vertical field-of-view. First documentation of the sickness appeared in Wenger (1980), who reported that nearly all flight engineers, but not pilots and copilots, experienced sickness. Flight engineers are seated in a position such that their view of the pilot/copilot displays is off-axis and therefore optically distorted. Furthermore, the display edges are visible, giving inappropriate near-field cues in the infinity scene. Pilots and copilots view their displays from an on-axis perspective and as such, do not experience these distortions. Wenger reported that acute symptoms consisted of dizziness, yawning, burping, confusion, unsteadiness, and nausea, typically leading to mission aborts after 40 minutes. Furthermore, residual effects including illusory spots in the visual field, disorientation, and imbalance made simulator exit and subsequent locomotion risky. Sickness occurred with or without the motion base activated and usually only in the flight engineer. Attesting to the device-specificity of the simulator sickness problem, Wenger reported that a virtually identical P-3C simulator with a model board closed-circuit TV display rather than a computer-generated display, did not produce appreciable simulator sickness. Other potential problems noted about the simulation included the tendency of the physical motion system to lag display movement, even though both systems are initiated by the same electronic signal, and the presence of visual cues indicating that the infinity optics images are really only a few feet away. In addition to hardware remedies of these problems, Wenger recommended that countermeasures should include a minimization of head movements in the simulator, encouragement of flight engineers to focus attention on their tasks and not on malaise, and deactivation of the motion-base with inexperienced flight engineers. Occluding the flight engineer's view of the frontal displays was also performed. This resulted in reduction, but not elimination, of the simulator sickness problem.

In another Navy correspondence, (COMPATWINGSLANT, 1980) the 2F87F flight engineer's disorientation and sickness was reiterated and again attributed to the lack of an appropriate display. Request for a center forward visual display was made and this issue was the subject of a research investigation conducted by Crosby and Kennedy (1982), discussed in the Experimentation Reports section of this review.

Kennedy (1981) found that coupled (to the tactical trainer) missions in the 2F87F which included minimal visual cues (e.g., IFR conditions), provoked much less sickness in the flight engineers than uncoupled missions, which required considerable visual input, especially for take-off and landing. Kennedy also reported that a simple baffle-occluder for the flight engineer greatly reduced the simulator sickness problem, as it occluded most or all of the pilot/copilot visual scene from the engineer's view. Post-flight ataxia problems were noted in no-baffle conditions for the flight engineers and also to some degree for pilots, who always viewed one forward and one side display, but not for copilots, who viewed only a forward display. Postural equilibrium difficulties were reported only on flights of longer than one hour duration. Furthermore, Kennedy astutely noted that highly experienced (e.g., 2500 hours or more) flight engineers may exhibit very low baseline postural equilibrium scores, which can be a deleterious result of vestibular stresses coinciding with flight exposure, such as ambient noise and hyperbaric effects. If this loss of auditory and nonacoustic labyrinthine sensitivity among flight engineers in this reciprocating engine aircraft is occurrent, then it may account for the <u>higher</u> prevalence of sickness and disequilibrium among <u>less</u>

experienced engineers in the 2F87F. In many other simulators, reports are that sickness is higher with experienced aircrew members (commensurate with the perceptual conflict hypothesis), but in the P-3C, experienced aircrew may have more hearing/vestibular sensory loss due to the particular aircraft's turboprop drone (or other stressors) and therefore have more inherent protection from motion sickness symptomatology (Kennedy, 1981).

Canadian Aurora simulator sickness. Money (1980) documented the incidence of pilot and flight engineer sickness in the Aurora CP140 moving-base flight trainer with computer-generated visuals. Symptoms ranged from mild discomfort to slight nausea in 6 of the 14 aircrew, while no severe nausea or emesis was exhibited. Sickness was prevalent among experienced pilots. Sickness occurred only during initial flights in most trainees, who consistently reported that conflict or lack of correspondence between visual and motion feedback influenced their malaise. Money noted two situations in which the conflict is salient: 1) a taxi turn of 180 degrees is depicted visually by yaw and change in lateral position in the scene, however, the vestibular receptors do not sense the same turn because the simulator's motion base cannot produce a full 180 degree rotation and/or it may not produce the same rate of rotation within its excursion limits as in the visual depiction; 2) a sustained banked turn is represented by angle of bank in the scene and rotation of visual scene in the opposite direction, but the motion system cannot produce a sustained resultant acceleration cue of "pulling g." In these and other situations, the nonacoustic labyrinth may not be fooled and a vestibular/visual conflict arises.

Money reported that some simulator users deactivate their device's motion base in VFR flight scenarios because they believe it is only useful for IFR training and because they fear that the addition of physical motions contributes to sickness. There appears to be considerable agreement in the training community about the former assumption and the latter appears to be quite simulator-specific. There is some strong evidence that sickness induced by visually-depicted motions may be obviated by the addition of proper motion cues (e.g., Sinacori, 1967). And in some simulators known to induce sickness, such as the Marine Corps 2F117 (CH-46E) and 2F121 (CH-53D) helicopter devices (e.g., Kennedy, Dutton et al., 1984), the incidence of sickness in Visual Flight Rules (VFR) conditions is reported by instructor pilots to be higher with motion off and visuals on. However, with fixed-base simulators as noted by Puig (1970), if strong distortions are present, resulting in discrepancies within the visual cue presentation, addition of inertial cues cannot be expected to correct the sickness problem and may, in fact, aggravate it. Furthermore, in a high performance Air Force tactical simulator without visual, the use of the motion system (presenting vestibular stimulation in the absence of vection) was associated with greater trainee nausea (Hall and Parker, 1967).

For coping with the Aurora sickness problem, Money (1980) recommended several procedural countermeasures to be used until trainees adapted to the simulator and symptoms subsided. These suggestions included (among others): seating the trainee before activating the scene; minimizing use of freeze (stop-action) and reset (rapid slewing of visuals ahead or back in time); minimizing taxi turns, turbulence, clear-hood flying, and sudden altitude and speed changes; minimizing the necessity of pilot head movements; increasing nauseogenic stress gradually with each flight; providing anti-motion sickness drugs (realizing their side effects); and, as a final resort, deactivating the inertial motion system.

<u>Fighter simulator sickness</u>. Several authors have noted the incidence of aircrew sickness in simulations of F-14 and F-4 fighter aircraft, which are fixed-base devices with 350 degree horizontal field-of-view point-light source dome display of sky/earth background and camera model targets. The first formal report (Frank, 1981) of sickness in the Navy F-14 weapons systems trainer (designated 2F112) was that 10% of aircrew members experienced some symptoms of simulator sickness. Later in 1981, FITRON 124 reported that the 2F112 induced aircrew sickness and sensorimotor aftereffects, particularly on the first simulator exposure, which necessitated a post-flight readjustment period. Readjustment guidelines were set forth in the interest of safety and included the following: 1) no flight in actual aircraft for at least 12 hours after initial flight in the 2F112 (and preferably after a night's sleep), and 2) on second and following simulator flights, a waiting period of two or more hours before actual flight. These measures certainly attest to the potential serious ramifications of the wide field-of-view simulator aftereffects surfacing during actual flight. Furthermore, a problem noted by other users in previous simulator reports, that of visual situation freeze in off-horizon attitudes, was addressed in FITRON's operational guidelines. It was suggested that freeze only be implemented in earth horizontal, wings-level attitude and that the dome scene be flooded with white light (masking scene content) during entry and exit. Also, aircrews were instructed to don a flight suit, g-suit, and torso harness while in the simulator.

In another wide-angle dome display fighter simulator of similar overall design to the 2F112, the Navy 2E6 Air Combat Maneuvering (ACM) simulator, sickness symptoms including nausea, dizziness, disorientation, and delayed reactions were reported for both pilots and back-seat radar intercept officers (RIOs)(Casto, 1982). Again, experienced aircrew were found to be most susceptible. One potential factor contributing to the disorientation experienced in the 2E6 and 2F112 fighter simulators was that the point-light source projection dome displays did not provide strong visual altitude nor relative heading and velocity cues with respect to the terrain. These cues are usually more compelling in simulations using computer-generated imaging techniques.

Countermeasures for reducing sickness in the 2E6 noted by Casto (1982) paralleled those set forth by FITRON 124 (1981) for the 2F112. Due to the prevalence of the sickness problem in the 2E6 simulator, it was the subject of more extensive study by McGuiness et al. (1981), discussed in the Experimentation Reports section.

Other aircraft incidence reports. There are also scattered reports of aircraft simulator sickness. Frank (1981) relayed that 48% of 21 aircrew in the Navy E-2C turboprop simulator (device 2F110) experienced some symptoms of discomfort. The six degree-of-freedom moving-base device has a computer-generated visual scene of approximately 139 degrees horizontal by 35 degrees vertical. Copilots (who have fewer visuals) seemed to be more susceptible to sickness than pilots, and experienced aircrew more so than the inexperienced. Frank and Crosby (1982), in a preliminary evaluation, predicted the potential for sickness in the 2F117A six degree-of-freedom moving-base, CGI simulation of the CH-46E dual-rotor helicopter. Problems such as discontinuity in displayed horizon, display flicker, and defocused, distorted visual cues for the copilot and instructor, who are not sitting in an optimal position to view the displays designed for the pilot, were offered as potential etiological factors. Since the time of their preliminary evaluation, the sickness potential noted by Frank and Crosby (1982) has been verified in the 2F117A (CH-46E) and its sister device, the 2F121(CH-53D), having incidence rates (sample sizes) of approximately 29% (160) and 36% (208) as reported by Kennedy, Dutton et al. (1984).

Incidence in Driving Simulators

Because driving simulators incorporate many of the same technologies as used in flight simulation to create the illusion of vehicle motion, their etiological bases for operator sickness are likely quite similar to those of aircraft simulator sickness. The following discussion is limited to driving simulators which are unprogrammed, interactive, and employ the driver "in the control loop." Some of these devices, primarily used for research and design purposes, are known to induce subject discomfort (Casali, 1981). Other driving "trainers" which utilize programmed film or videotape roadway sequences are not truly interactive because the driver's control inputs are not used to modify the feedback cues. Due to the fact that the driver of these latter devices does not function in an error-nulling capacity, these devices cannot be classified as vehicular control simulators and as such are not covered herein.

Fixed-base driving simulator sickness. The first reports of driving simulator sickness appeared in Barrett and Nelson (1965) who reported that 11 (44%) of 25 driving subjects became too ill to finish a simulator evaluation study, 2 (8%) vomited, and of the 14 subjects who did finish, 5 (36%) became nauseated while driving. Consistent results were also reported by Barrett, Kobayashi, and Fox (1968). The fixed-base simulator used in these studies incorporated a terrain-board objective, closed-circuit TV system, with the image displayed via a Schmidt large-screen TV projection of field-of-view 50 degrees horizontal by 39 degrees vertical. Another version of this same simulator utilized an infinity optics virtual image CRT display of slightly wider visual field than the TV projection system (Barrett and Nelson, 1966). This device was associated with a greater (though not statistically-significant) percentage of drivers (56%) who could not complete the study. Barrett and Nelson (1966) noted that each display system, though neither constituted a wide field-of-view, had certain anomalies, such as distortion near the edges of the CRT and the appearance of seams between adjoining sections of the projection screen. Resolution was approximately equal for the two systems while contrast was reported as poorer for the projected display. In subsequent applied research with these simulators, they were notorious for inducing subject malaise.

Two other fixed-base driving simulators known to produce sickness were located at the University of California at Los Angeles (UCLA). In one of these devices, the display consisted of a TV-projected image of an endless belt roadway model of approximately 40 degrees horizontal field-of-view. After long driving periods, this simulator was known to induce vertigo (Jex and Ringland, 1973). The other UCLA device utilized a flat-screen motion picture display having 150 degrees horizontal field-of-view forward and 45 degrees rearward (Jex and Ringland, 1973). In displays of this type, dynamic distortions are usually apparent if the driving subject does not closely follow the path assumed by the camera car in shooting the roadway film. Testa (1969) reported that subjects in this simulator exhibited perspiration and respiration changes indicative of sickness onset and also that they indicated feelings of sickness on a post-drive questionnaire. Jex and Ringland (1973) also documented the prevalence of sickness in this wide-screen simulator.

Finally, a fixed-base, point-light source display driving simulator called the Link Sim-L-Car, which was popular in the 1970's, was known to induce long-term vertigo in some drivers (Jex and Ringland, 1973). The roadway image in this device was somewhat blurred, unclear in detail, and gave the visual impression of driving at dusk.

Moving-base driving simulator sickness. Early reports of high incidence of sickness induced by fixed-base driving simulators led to the postulation by several authors that cue conflict, resulting from the absence of physical motions paralleling visual apparent movements, precipitated sickness. This gave rise to the need for motion cuing systems in driving simulators, the fundamental question being how much motion was necessary. This is evidenced in the Barrett and Thornton (1968b, p. 307) observation that "An interesting question is the degree of motion required to give the necessary body cues. Simple random vibration [in lieu of inertial cues] may be enough to eliminate the cue conflict, a possibility having considerable practical and economic import for the simulation art." However, as exemplified by the early UCLA simulators (e.g., Testa, 1969), and the newer Federal Highway driving simulator, (Stephens, 1985) both of which have had some subject discomfort problems, the addition of random platform vibration alone is not enough to eliminate the conflict. Nor may the visual/vestibular conflict that is assumed to be present in fixed-base devices be strong enough to induce sickness in all simulators. For instance, McLane and Wierwille (1975) deactivated the motion base of a CGI display (48 degrees horizontal by 30 degrees vertical) driving simulator, and found no reports of sickness in the fixed-base mode. It is noteworthy that this particular simulator, in existence since initially designed and built in 1971, has not induced simulator sickness in subject drivers in approximately 20 applied studies using various driving scenarios and durations. The device is normally operated with a roll, yaw, lateral translation, longitudinal translation motion base and is further described in Wierwille (1975).

As motion bases capable of generating accelerative and positional cues analogous to those experienced on the road began to appear in driving simulators, incidental reports of subject malaise were still prevalent. Two documented cases appearing in the open literature concerned acute illness in several subjects in a North American Rockwell driving simulator using a narrow field-of-view (39 degrees horizontal) TV projection display (Breda, Kirkpatrick, and Shaffer, 1972), and sickness in an early General Motors Technical Center device, using a 70 degree wide motion picture display (Beinke and Williams, 1968; Jex and Ringland, 1973). Both of these devices utilized the technique of attempting to convey lateral and longitudinal acceleration forces by providing oversized tilt in roll and pitch, respectively. As discussed earlier in the context of perceptual conflict, this practice may be problematic in that the subject anticipates a translational accelerative cue, but senses the rotational aspect of the simulated cue, due to the tilt of the head with reference to the gravity vector. This may give rise to an intra-vestibular (canal/otolith) conflict as well as a visual/vestibular conflict, in that displayed translational motions are accompanied by rotational inertial cues.

IV. RESEARCH ON INDIVIDUAL DIFFERENCES

Due to the hindrance imposed by the early incidences of simulator sickness, several researchers in the late 1960's began to concentrate on individual differences among subjects as they related to sickness.

Perceptual Style

Most of the early research was performed on the basis of individuals' perceptual style on a continuum of field independence-field dependence, as measured by such instruments as the rod-and-frame test (RFT), the body adjustment test (BAT), the embedded figures test (EFT), and the hidden figures test (HFT). Persons found to have a field-dependent manner of perception tend to conform to, or are influenced by, the prevailing field or environment while field-independent individuals tend to perceive their environments in analytical rather than global fashion, separating the background from objects of interest and relying on bodily cues.

Barrett and others conducted a series of experiments aimed at determining the relationship between perceptual style, simulator sickness, and other related issues. Based on the rationale that sickness experienced in their fixed-base simulator, described in Barrett and Nelson (1965, 1966), was due to a sensory conflict between the visual presentation of motion and the lack of any corresponding bodily motion, Barrett and Thornton (1968b) hypothesized that field-independent subjects, being more sensitive to bodily cues and therefore the conflict, would be more susceptible to sickness. In their study directed specifically at simulator sickness, Barrett and Thornton (1968b) classified subjects' perceptual style on the RFT, had them drive the simulator, and obtained questionnaire measures reflecting simulator discomfort. (Basically, the RFT is a test where subjects adjust a rod, which may be tilted, inside a frame, which also may be tilted, to the perceived vertical.) Attesting to the hypothesis set forth, all subjects who were classified as "extremely field independent" (i.e., could accurately adjust the rod) experienced such discomfort that they had to exit the simulator prior to completion of the driving task. In all, half of the subjects in the study could not complete all driving trials; somewhat surprisingly this included three "extremely field dependent" subjects. As indicated on the RFT, field independence scores were found to be positively correlated with simulator sickness (Pearson $\underline{r} = 0.52$, $\underline{p} < 0.001$). Some subjects reported that they experienced sickness symptoms for up to 48 hours following the simulated driving task. Similar findings were reported by Testa (1969), using the UCLA motion picture, fixed-base simulator discussed earlier.

In a separate study concerning driver emergency reactions using the same simulator, Barrett and Thornton (1968a) again (see above) found that over half of their subjects had to quit due to discomfort. This study, while not aimed directly at simulator sickness, clearly demonstrated that its occurrence severely compromised the research results. This was best evidenced by the fact that simulator sickness yielded a high positive correlation with degradation of subjects' abilities to decelerate properly in an emergency.

The relationship of perceptual style to simulator sickness appears to be sensitive to the particular test used to measure field independence-dependence. As noted by Barrett, Thornton, and Cabe (1969), Pearson $\underline{r}$ correlations between RFT scores and sickness metrics were between 0.33 and 0.55, while between EFT (a tabletop geometric figure-background disembedding test) scores and sickness the correlations were much less compelling (0.10 to 0.29). Barrett et al. offered several explanations for this occurrence, including the lower reliability of the EFT as compared to the RFT. Finally, in a study of moving-base driving simulator discomfort, Casali and Wierwille (1980) pre-matched subjects to experimental conditions on the basis of their scores on the HFT, an achromatic paper-pencil analogue to the EFT. Post-hoc analysis of variance procedures showed that demonstrated differences in the simulator discomfort metrics were not attributable to subject position on the field independence-dependence continuum measured by the HFT (Casali, 1979). Perhaps the HFT was not as sensitive as the RFT or BAT and therefore did not tap true perceptual style differences among subjects. Or it could well be that the cue conflicts inherent in the Casali and Wierwille moving-base simulator degraded conditions were not as salient as the visual/vestibular conflicts in the Barrett and Nelson (1965, 1966) fixed-based simulator studies, therefore their effect simply did not depend on the subjects' perceptual styles. This latter explanation is certainly plausible given that no serious discomfort or early simulator exit occurred in the Casali and Wierwille study as contrasted with the more severe sickness experienced by Barrett's (and others') subjects.

Though not simulator-based, several other research findings on perceptual style have bearing on the metric's utility as a predictor of sickness susceptibility. Using a swing-type experimental apparatus designed specifically to elicit cue conflict in passive observers, Barrett, Thornton, and Cabe (1970) found that extremely field-dependent subjects, as measured on the RFT but not the HFT, experienced greater sickness symptoms than field-independent subjects. In terms of conflict theory and its relation to perceptual style and sickness, this result was exactly opposite that found in the Barrett et al. (e.g., 1968b) simulator studies and in direct conflict with their predictions. Barrett et al. (1970) offered several after-the-fact explanations, such as that field-dependent individuals are more suggestible (and therefore more likely to believe that their swing was actually moving), and due to the administration of a questionnaire on discomfort, they may have felt that they were expected to get sick, and therefore did. In a subsequent study, Alexander and Barrett (1975) addressed a related problem with active/passive observers. They first classified subjects according to RFT and HFT scores and then presented a film to each subject which depicted fast driving in a rural setting. Half of the subjects were told to simply view the film in a passive sense while the other half were instructed to perform foot movements in antici-pation of the car's direction. The results were somewhat in conflict with those of others, that is, in the passive viewing condition, field-independent subjects reported more sensations of discomfort than field-dependents. For the interested reader, a critique of the literature on perceptual style and simulator sickness may be found in Frank and Casali (1986).

In summary, it appears that the use of metrics of perceptual style to predict individual susceptibility to simulator sickness has some promise but is in need of further study. The validity of the field independence-dependence measure in reflecting a person's susceptibility to sickness appears to be quite situation-specific, as evidenced by several conflicting results, and possibly simulator-specific. Furthermore, the application of different tests of perceptual style (e.g., BAT, RFT, EFT, HFT), as well as the manner in which they are administered, tends to produce some discrepancy in results. Therefore, test selection must be made with extreme care. For example, while both the RFT and HFT are proposed to be indicants of perceptual style, as noted by Barrett et al. (1970), the tests' failure to correlate indicates that they are tapping two distinct perceptual dimensions. These are critical issues which must be answered if in future studies of simulator sickness, attempts are made to control inter-subject variability with respect to perceptual style.

Other Individual Differences

While most individual difference research has addressed perceptual style, Reason and Diaz (1971) investigated several other variables in a fixed-base, point-light source display driving simulator study. The study was unique in that subjects were seated as passengers, not drivers, in the simulator. After a 10-minute drive, 28 (90%) of 31 subjects reported some symptoms of sickness. Half of the subjects wore "blinders", reducing their horizontal field-of-view to obscure all peripheral visual cues except for the roadway display (a reduction from about 90 to 45 degrees). This restriction did not significantly influence the level of discomfort in response to the simulator task. Subjects also rated the realism of the simulator and in most cases, there was a negative correlation between reported sickness and rated simulator realism. In keeping with the conflict theory, subjects who perceived the simulator to be of low fidelity may have been more sensitive to discrepancies between the device and their automobiles, giving rise to conflict with their ingrained expectancies. Furthermore, Reason and Diaz found a positive relationship between subjects' experience as drivers and passengers in vehicles and their susceptibility to simulator sickness. Therefore, the usual positive relation between simulator sickness and aircrew experience (e.g., Frank et al., 1983) also appears to hold for passive observers (passengers) in ground vehicle simulators. This connection between prior experience with the actual vehicle and simulator sickness susceptibility appears to be the most well-documented individual difference relationship associated with the sickness problem.

Past history of motion sickness experience, as inventoried using the Motion Sickness Questionnaire, was not found to be reliably predictive of sickness in the simulator, according to the Reason and Diaz (1971) study. Its prime utility was in targeting subjects who were highly susceptible, but it offered little discriminant capability among those of moderate susceptibility. Finally, women were reported to be significantly more susceptible to simulator discomfort than men. In similar vein, Money (1970) documented seven studies which indicate that on average, females are more susceptible to motion sickness than males.

EXPERIMENTATION REPORTS

As previously mentioned in the section on "incidence reports," most of the literature on simulator sickness has consisted simply of the documentation of its occurrence accompanying simulator use. However, several reports which are reviewed in this section describe research studies which have addressed simulator sickness in an experimental framework. Of these studies, some have involved the specific manipulation of independent variables and their effects on subject illness and performance. These are discussed in the following subsection. Next, research studies which have addressed simulator sickness in a more global sense, for example, by surveying in systematic fashion its symptomatology and frequency in a variety of devices, but not involving the control of independent variables in the classic sense, are discussed.

Research on Independent Variables

Miller and Goodson (1958). These authors performed a study to investigate simulator sickness in the previously-described fixed-base, point-light source 2FH2 helicopter simulator, found to be problematic by Havron and Butler (1957). The problem which appeared most prominent and experimentally-accessible was the lack of retinal disparity and poor depth convergence caused by distorted distance cues. This was studied by occluding vision in one eye of subjects, eliminating the binocular depth cues. Using ten pilot trainees, flying with and without the occluder, no differences were found between the binocular and monocular viewing conditions, evidencing that the distortion in distance cuing was probably not sufficient, by itself, to elicit sickness. Many other simulator hardware problems, noted previously in the reviews of Havron and Butler (1957) and Miller and Goodson (1960), were in need of study, however, the author indicated that time was not available to study them. Miller and Goodson (1958) estimated that two years would have been necessary to perform controlled experiments addressing all problems.

Parker (1964). While his study was not simulator-based, Parker clearly demonstrated that neither vestibular stimulation produced by physical motion nor active involvement in a visually-presented motion scenario was necessary for inducing motion sickness symptoms. The experimental situation was similar to that of the automobile simulator passenger situation in the Reason and Diaz (1971) study on individual differences, with the major distinction being that Parker's subjects viewed rapid vehicle driving from a chair rather than from inside a car. Even so, the view was from an "inside-out" perspective. Parker found that when the driving film was presented in the forward (normal) manner, clear changes in a number of autonomically-mediated variables from baseline values were found, evidencing the onset of motion sickness symptoms. However, when the film was run backward (motion-reversed), little response change was observed. From a perceptual conflict standpoint, one explanation for this difference is that the motion-reversed film depicts an unfamiliar situation, less compelling and less sensorially-involving than the forward motion film. Because the reverse motion is atypical, associated response expectancies have not been ingrained so conflicts are not as salient, and therefore not as sickness-evoking, as for the more familiar forward motion situation.

Casali and Wierwille (1980). This study comprised a factorial experiment aimed at determining the effects of three driving simulator design variables on simulator sickness. A typical driving task was presented in the moving-base Virginia Tech simulator, described previously. In a between-subjects experimental design, 64 subjects were matched according to perceptual style and exposed to one combination of the following independent variables:

1) Technique of simulating lateral translational motion:
   a. by actual translation (standard method)
   b. by tilt in roll axis (alternative method)

2) Delay in visual and motion systems in response to steering input:
   a. nondelayed (standard vehicle dynamics)
   b. delayed (300 msec smoothed delay)

3) Simulator platform:
   a. subject unenclosed (standard method)
   b. subject fully enclosed in cab (alternative method)

Eight dependent measures of driver discomfort and driving task performance were obtained and analyzed using multivariate procedures. In the "standard" conditions of the independent variables, no indications of simulator discomfort nor driving performance problems were found. However, several important effects were attributable to the non-standard conditions. "Tilt" simulation of lateral acceleration cues was associated with significantly higher pallor and respiration rate in subjects, while also affecting vehicle path control by inhibiting subjects' steering reversals. As earlier discussed, such alternative techniques of simulating linear accelerations can create cue conflict when the subject senses the rotational aspect of the motion, which is an artifact.

The presence of simulated computational dynamics delay was found to induce mild uneasiness and also increase vehicle yaw deviation. In conditions of delayed feedback, many subjects reported that the simulator did not react as quickly as their cars did and was more difficult to control. With the presence of delay in addition to normal vehicle response delay, such as that resulting from serial processing throughput in a simulator's computational systems, the operator is burdened with the task of introducing considerable lead compensation in anticipation of the simulator's lagging response. In this situation, driver expectancy may be discrepant with simulator response, and vehicle control behavior may be oscillatory, having a disconcerting effect.

Finally, the box-like cab, which enclosed the subject, appeared to be disquieting in terms of heightened respiration rates and forehead perspiration. Other driving simulators employing similar cabs (e.g., Beinke and Williams, 1968) have exhibited discomfort problems, while the Virginia Tech simulator, running in its typical unenclosed configuration, has not.

The basis for such a cab influence, if it indeed exists, is unclear. It can be speculated that the cab has a claustrophobic effect (e.g., Havron and Butler, 1957), as drivers are used to a "greenhouse" situation in the actual automobile, when visual cues are apparent through the side and rear windows, not just through the windshield as in the cabbed simulator. Furthermore, the cab eliminates any ground reference cues from the room that may serve as a stabilizing influence upon the subject. Inside the cab, the CRT display may appear to float in dark space because of the lack of peripheral horizon cues. Some subjects in the Casali and Wierwille (1980) study commented that they believed that they became disoriented in the cab due to this "floating display" effect. This was not a problem in the uncabbed condition, even though the simulator was run in the dark, perhaps because the subject may have been aware of shadows in the room which served as an external frame of reference.

Other authors (Gibson, 1950; Puig, 1970) have noted that without a definite visual frame of reference, observers may have difficulty in distinguishing the visual field from the "visual world." In this case, an artificial, illusory frame of reference, such as the lower horizontal edge of a roadway CRT display, may be adopted. Gibson stressed that disequilibrium and discomfort may result from such an illusory reference which dominates visual perception.

SAAC studies (1976; 1980). Hartman and Hatsell (1976) administered a structured rating scale to approximately 100 instructor pilots after they flew the multiple CGI-CRT "mosaic" display SAAC simulator (described earlier) to ascertain the contributors to and symptoms of the sickness problem. While independent variables were not manipulated in the strict sense, the field study yielded important findings regarding several simulator design characteristics. The following simulator-induced symptoms, together with the percentage of pilots experiencing them, accompanied the use of the SAAC: 1) spatial disorientation (52%)--reported on first flights only, with motion on or off; 2) eye strain (50%)--possibly due to visible CRT raster lines generating accommodative conflict between near-vision cues with desired infinity perspective, and also resolution and luminance discrepancies between CRTs; 3) headaches (32%)--possibly resulting from the eyestrain; 4) tiredness (38%)--from the high air combat workload; and 5) nausea (14%)--reported as occurring with or without motion and decreasing with the number of missions, resulting in full emesis in two subjects.

Two major recommendations toward alleviating simulator sickness arose from the study's results. One was that the motion base quality warranted improvement in that acceleration and displacement amplitude should be increased, movement-onset delays should be minimized (less than 0.1 second), and the visual/motion systems should be synchronized to reduce oversensitivity in the control dynamics, possibly by using damped equations of motions. The second recommendation relied upon the demonstrated occurrence that a known stimulus for inducing sickness is 0.2 Hz to 0.4 Hz vertical periodic motion (O'Hanlon and McCauley, 1974). From a time-series spectral analysis of a filmed sequence of SAAC motion, the authors discovered that motion-base accelerative energy was quite high in the critical 0.2 to 0.4 Hz range and recommended that motion base resonant frequencies be raised, if due to motion buffer characteristics, by adjusting the buffer region onset to a point close to the excursion limits.

Expanding on the SAAC investigations by Hartman and Hatsell, Kellogg et al. (1980) performed an interview-based study on pilot trainees involved in an intense one-week SAAC course on air-to-air combat. (In contrast to the Hartman and Hatsell study, Kellogg, et al. conducted their SAAC study with the motion-base <u>off</u> as it is currently usually used in training.) The major independent variables were F-4 flying experience level and training duration. The results showed adverse symptoms in 42 pilots (87%) of the sample of 48, with experienced pilots undergoing the worst reactions. Nausea was prevalent during the first two days of training and then markedly curtailed by the end of the week, especially when pilots were able to get a good night's sleep between simulator exposures. Also, profuse sweating, imbalance, and dyskinesia were common acute and residual symptoms. Spinning sensations and kinesthetic aftereffects which were representative of flashbacks to specific in-simulator maneuvers also were experienced. Over 30% of subjects reported vivid visual flashbacks, dreams, or post-simulator attentional difficulties which persisted throughout the training week. An aftereffect not often reported with other simulators, periodic inversion of the visual field, was experienced by 10% of the subjects. In rating their fatigue, 79% of the trainees rated mental fatigue as higher in the simulator while 70% rated physical fatigue as higher in the actual aircraft. The former result may be explained by perceptual conflict arising in the pilot due to the strong linear and circular vection portrayed by the wide, detailed display, coupled with the lack of corresponding vestibular cues. The latter result may be due to the high physical workload imposed by g-loading in the aircraft.

Kellogg et al. (1980) also noted that sudden freezing of the visual screen and the practice of displaying visuals upon ingress seemed to raise considerable cognitive dissonance among some trainees, potentially contributing to spatial disorientation and sickness. This effect appears to be most profound in wide-screen displays, such as that of the SAAC, capable of depicting compelling positional, velocity, and acceleration cues via the use of peripheral detail and "streaming," and ground growth and progression. The freeze feature, being a useful training tool, is often utilized in many simulators, but it apparently can be expected to cause trainee discomfort if not used judiciously.

<u>P-3C studies (1978; 1982)</u>. As mentioned earlier, the Navy P-3C simulator (device 2F87F) has a considerable history of simulator sickness in its trainees. Ryan, Scott, and Browning (1978) conducted a study investigating the effects of cockpit motion versus no motion on simulator sickness as measured via a motion sickness questionnaire (MSQ). According to motion sickness historical data from the MSQ, subjects in the motion and no motion groups appeared to be about average among pilots with regard to sickness susceptibility. Neither group, however, produced significant evidence of simulator-induced sickness during training. Even though it did not seem to alleviate nor contribute to sickness, physical motion was preferred (over no motion) by instructor and student pilots alike. It should be noted that the

2F87F simulator used in Ryan et al. (1978) was a TV camera model board version rather than the more problematic CGI version discussed in Kennedy (1981) and Crosby and Kennedy (1982). The earlier model board version provided a wide field-of-view for the pilot, copilot, and flight engineer. In the newer CGI version (e.g., at NAS Brunswick), the pilot/copilot displays are designed for their use alone, but the flight engineers can view the displays as well, but at a 30 degree off-axis position.

Based on complaints of flight engineer sickness especially during high-detail visual scenarios, (but generally favorable reactions from pilots and copilots), Crosby and Kennedy (1982) conducted a two-phase study of the simulator sickness problem. In the first phase, the 2F87F was unmodified and run in both motion-on and motion-off modes of operation. Paralleling the earlier findings of McLane and Wierwille (1975) and Ryan et al. (1978), no differences in postural equilibrium measures were found between the motion versus no motion conditions. However, within each condition there were significant degradations in post-exposure ataxia test performance from pre-exposure levels.

The simple addition of a baffle to occlude the flight engineer from view of the pilot/copilot displays significantly reduced the incidence of disequilibrium. In the second phase, a low-fidelity monochrome CRT display was added strictly for the flight engineer, which provided a duplicate of the pilots' visual scene. This display reiterated the effect of the baffle in alleviating flight engineer problems, but afforded the additional advantage that the flight engineer received a VFR presentation. This study clearly demonstrated that certain etiological aspects of simulator sickness are simulator-specific, and that at least in some cases, relatively simple, inexpensive retrofits may largely eliminate the distortion conflicts, thereby alleviating the sickness.

Field Survey Research

McGuiness et al. (1981). Using the fixed-base F-4/F-14 ACM simulator (device 2E6) with point-light source projection dome display, 66 aircrew members were sampled using a questionnaire to ascertain the incidence and severity of simulator sickness. Though typical training missions on the 2E6 were relatively unstructured and variable in length due to the lack of a formal training syllabus, subjects in this study were presented with four simulator flights of one hour each to give some degree of control to the assessment process. The results of the study revealed that sickness incidence was 27%, with the highest incidence rate (47%) among aircrew members with greater than 1500 hours experience and 18% among aircrew members with less than 1500 hours. Pilots, who were actively controlling the simulated aircraft, were over twice as susceptible to sickness as Radar Intercept Officers (RIOs). The authors hypothesized that this may have been due to the fact that pilots are more conditioned (than the passively-observing RIOs) to react to expected vestibular and kinesthetic acceleration cues and when they do not receive such stimulation, a provocative conflict arises. Furthermore, RIOs receive T-39 backseat training (i.e., in the actual aircraft) which is conducive to air sickness, thereby possibly increasing their tolerance to motion sickness symptoms.

Typical acute symptoms found by McGuiness et al. included dizziness, nausea, vertigo, and the "leans," while "eyeball jitter," weak knees, loss of depth perception, and stomach fullness were reported less often. Interestingly, very few flashbacks or aftereffects and no emetic responses were reported, as in contrast to the CCI, moving-base SAAC simulator. One pilot who had considerable experience in both the 2E6 and the SAAC related that the SAAC CRT mosaic display was much more disturbing to his eyes and resulted in vivid visual flashbacks not experienced during the 2E6 training. While the SAAC and 2E6 ACM simulator appear to be similar from a training mission standpoint, they are, in fact, quite different in design and usage procedures. The CRT CGI displays of the SAAC are detailed, complex, and convey ground growth and progression to the pilot in contrast to the more impoverished point-source dome display of the 2E6. This perhaps causes a higher likelihood of "imprinting" the visual stimulation in the SAAC pilot, later causing flashbacks.

While the 2E6 display is of relatively low structure, inspection indicates that it is not distorted, except for some blur of objects portrayed on the transparency. Also, even with its near 360 degree field-of-view, the limited vection cues and potentially, the available ground reference cues (the simulator gantry handrails are left in view), may serve to limit the level of perceptual conflict produced by the simulator, accounting for the relatively low levels of sickness.

Finally, training hops in the SAAC are more intense (for a short period of time) and more structured than in the 2E6, possibly contributing to the much higher (87%) incidence of sickness (McGuiness et al., 1981).

Kennedy, Frank et al. (198[illegible]). Utilizing two six degree-of-freedom moving-base helicopter simulators (SH-[illegible] helicopter, device 2F106, and SH-3 helicopter, device 2F64C), both having infinity-optics CGI calligraphic displays, this study was aimed at testing an experimental test battery to be used in field studies addressing simulator sickness. Subjects (36 on the

2F64C and 28 on the 2F106) were given the Pensacola Motion Sickness Questionnaire (MSQ), postural equilibrium test, and a simulated air combat maneuvering (ACM) video-game performance test prior to simulated flight. Following simulated flight (the protocol for which was identical for both simulators), postural equilibrium and ACM tests were again administered to subjects, in addition to the acquisition of rating scale data and objective recordings of sickness signs and symptoms. No statistically-significant differences were found between measures obtained at the two simulators, so the data from the two sites were pooled and analyzed. On the rating scale, 8 (13%) of the 64 subjects reported that they experienced considerable uneasiness while 25 (40%) reported two or more symptoms of discomfort. The pre-post ataxia and ACM tests did not yield significant changes in subject performance due to simulator exposure but the MSQ was found to be mildly predictive of individual sickness susceptibility.

Based on the previous success of the pre-post ataxia tests in the P-3C simulator (Crosby and Kennedy, 1982), the authors suggested that such equilibrium measures are probably useful in tagging "meaningful" effects caused by a simulator experience. Their lack of sensitivity in the shorter duration helicopter simulator flights is a source of concern, but probably should not preclude them from consideration. Furthermore, the demonstrated insensitivity of the motor skills (ACM video game) tests led to the recommendation that pre-post exposure <u>cognitive</u> ability tests be included in future research.

Kennedy, Frank et al. (1984) also made the cogent observation that the reported prevalence of simulator sickness may largely be a function of the characteristics of the criterion variable. For instance, when self-report written questionnaires are completed by trainees and treated with strict anonymity, a higher incidence of sickness may likely result than if trainees must sign their questionnaires. Furthermore, if questionnaires are administered or interviews conducted by authority figures, such as higher-ranking military flight instructors, trainees may be more reluctant to disclose felt symptoms than if a civilian is conducting the survey. For standardization to occur in the assessment of simulator sickness, these types of factors must be carefully controlled.

Kennedy, Dutton, Ricard, and Frank (1984). Following the preliminary helicopter site surveys of Kennedy, Frank et al. (1984), a large-scale pioneering effort was undertaken to apply a simulator sickness test battery in sickness assessment at 12 Navy and Marine simulator sites. The battery included the MSQ, motion history questionnaire, sickness rating scale, and two pre-post exposure postural equilibrium tests of Kennedy, Frank et al. (1984), in addition to a unique automated, microprocessor-based set of pre-post exposure performance evaluation tests requiring information processing, cognitive reasoning, and manual motor skills. In their 1984 paper, Kennedy, Dutton, Ricard, and Frank (1984) reported preliminary results from their survey of more than 1000 aircrew members flying 15 to 30 minute simulator hops. (The data are currently undergoing further analyses.) The authors selected a symptomatology cutoff criterion level believed to be representative of that level of discomfort where "unwillingness to participate [would result] if the participation was strictly voluntary [on the part of the trainee]." Based on this criterion level, incidences of sickness were reported as high as 55% with the SH-3 simulator (device 2F64C) at Jacksonville, Florida. The Jacksonville 2F64C has been found to have a throughput delay (from control stick input to x,y,z positioning) of 155-340 msec (Evans, Scott, and Pfeiffer, 1984), with 98% of the delays ranging from 155-285 msec.

The postural equilibrium tests evidenced a reduction in test performance following simulator exposure in the 2E7, 2F87F, 2F64C, and 2F112 devices. These reductions could possibly be attributed to disquieting effects of the simulator experience, as one might expect scores on the post-test to be improved simply by the practice afforded by the pre-test. Data from the motion history questionnaire and microprocessor-based tests had not been analyzed, therefore, their sensitivity to simulator sickness still requires verification.

Also, based on a subset of their obtained data, Kennedy, Dutton, Ricard and Frank (1984), formulated a useful theoretical model relating the occurrence of simulator sickness to the sequence and kinematics of a simulator training scenario. Applicability of this model was informally verified using a graphical representation of sickness severity plotted as a function of the time course of training hops in the Navy F-18 (2E7) ACM simulator. The model predicts the following course of symptomatology: 1) during initial flights all trainees would be expected to experience some disquieting effects; 2) most trainees would, with a few flights, adapt and exhibit less effects; 3) with continued flights requiring more intense maneuvering and more complex kinematics, sickness incidence would increase; and 4) trainees would readapt to the new situations in step 3 and incidence would again subside. These steps accurately tracked the time course incidence of sickness in the 2E7 ACM simulator (Kennedy, Dutton, Ricard, and Frank, 1984) in which mission intensity often correlates with the level of maneuvering and kinematics (the third step in the model). However, in other non-ACM simulators, such as the

E-2C simulator (device 2F110) and various helicopter devices, pilots and instructors alike have related anecdotes to this author that the prevalence of sickness tends to be lower as mission intensity and workload increase. Perhaps this is due to the fact that in these latter devices, high mission intensity does not always equate with violent maneuvering, complicated kinematics, and illusory stimulation, all of which may be sickness-provocative. Or it could also be the case that during high workload situations, aircrew do indeed experience heightened sickness but simply muster the effort to deal with it, and also do not report it, due to the immediacy and criticality of the training situation. Finally, the authors suggested that the most severe training implications of the sickness problem lie with the fourth step (and beyond) in the theoretical model. This final period involves adaptation to the simulator and to its discrepancies with the aircraft. Therefore, the pilot may leave this phase with ill-advised habits that may result in negative transfer of training from the simulator to the aircraft.

POTENTIAL DESIGN ETIOLOGICAL FACTORS

From the preceding accounts of and research on simulator sickness, it is evident that the problem is polygenic and that its causes may be quite simulator-specific. Several factors which appear to be likely candidates as sickness-contributors can be considered as aspects of simulator design. The most prominent factors are reviewed in this section; the reader is also referred to the excellent reviews by Kennedy, Frank, and McCauley (1983), McCauley (1984), and Puig (1984).

Control Loop Lags and Delays

It is well-known that inappropriate temporal lags may exist between control input and resultant system output, either in visual feedback, motion-base updating, or both, in a simulator (e.g., Casali and Wierwille, 1980; Ricard and Puig, 1977; Seevers and Makinney, 1979). These control loop lags are inappropriate in the simulator if they are in excess of the normal control response lag inherent in the actual system's dynamics. They are a relatively common problem and are sometimes difficult to overcome, as they may emanate from a variety of sources in the simulator, such as serial processing time in digital computers for vehicle dynamics modeling, inertial effects in motion and visual systems, control input sampling rates, iteration rates of motion cuing algorithms and visual display generators, and analog-to-digital/digital-to-analog conversion rates.

Furthermore, the temporal problems may be of various types, for example, transport delay, exponential (first-order) lag, and second-order lag, all of which may degrade control and potentially result in discomfort problems (Puig, 1984). Though problematic, simple transport delay should not be considered in isolation, since the rise time and amplitude characteristics of more "smoothed" delays are also critical. In addition, the duration and profile of the delay may vary during simulator operation, depending upon the instantaneous load on the computational systems and memory storage. For example, visually-impoverished, high altitude, docile flight scenarios would likely impose less computational load than high-speed low-altitude terrain-following VFR flight. McCauley (1984) has pointed out that some flight simulators may exhibit lags of as high as 350 milliseconds in motion system response to control input.

Finally, it should be noted that delays may be differential between visual and motion-based feedback systems, either unintentionally or by design. Some devices are known to provide physical movement of the operator's seat which phase-leads visual scene motion slightly. This provides a slightly early cue to the semicircular canals, which in turn provide cues regarding angular speed of the head that allow the change in rotational position to be sensed by integration or differentiation with other sensory afferent information (Benson, 1978; McCauley, 1984). According to this rationale, if physical motion lags visual input, the chance for conflict is greater, particularly for experienced pilots who may be much more sensitive to temporal discrepancies in visual-motion coupling.

Inappropriate control-feedback delays and lags are known to degrade controllability and stability of vehicular systems (e.g., Casali and Wierwille, 1980), and as Puig (1984) noted, may induce symptoms of sickness. First, the closed-loop delay places the extra burden on the human operator of having to "anticipate" system response and introduce compensating lead to control the system. This increases workload, effort, and may contribute to symptoms indicative of discomfort, anxiety, and/or increased exertion. With long time delays, humans may eventually learn to anticipate and compensate, but particularly for experienced pilots, who have ingrained expectancies about system response, the perceptual conflict may be too stressful. Furthermore, the simulator pilot (or driver) may adopt control behaviors that lead to pilot-induced oscillations (PIOs). Such oscillations may further contribute to sickness-onset as the vehicle motions (displayed visually and/or inertially) are no longer of random form but behave in a more sinusoidal fashion.

Other Dynamic Inaccuracies

In addition to control loop feedback delays, there are other dynamic inaccuracies that may exist in a simulator's computational systems that have the potential of degrading fidelity and influencing operator discomfort. These may emanate from several sources.

First, the mathematical model including the equations of motion for the actual aircraft or automobile must be valid and representative of that vehicle, at least within the intended limits of operation of the simulator. Given an accurate mathematical model, the software simulation of that model must also be correct and computing power must be sufficient to solve the simulation in rapid fashion, to avoid problems of delay and priority of update information, especially when that information must be used in sequential computations. To ascertain the dynamics of the actual vehicle being simulated, the optimal approach is to instrument the vehicle and obtain objective measures of vehicle performance under a variety of maneuvers and conditions which are anticipated for the simulation. However, the vehicular dynamics equations used in some simulators are not from the analogue full-scale vehicle, but are parameter-adjusted versions from those of other vehicles, often "tuned" with the aid of expert operators until vehicle handling "feels" correct. Others may utilize dynamics obtained from instrumented vehicle models, such as those used in wind-tunnel testing, or may extrapolate from a general set of vehicular equations of motion. In any case, proper modeling of the full-scale vehicle in the simulator's computational systems is perhaps the most fundamental and critical factor underlying the dynamics fidelity of the device. Furthermore, with respect to provocation of simulator sickness, it appears that the envelope of accurate correspondence between the simulator's dynamics and those of the actual vehicle must extend to low-speed maneuvers as well as those involving more complex high-speed kinematics. For instance, the author has observed that sickness can be elicited during slow driving simulator maneuvers, such as those involved in stopping and turning on city streets, and also during relatively stationary helicopter maneuvers, such as hovering near ground.

Other dynamic inaccuracies may arise as a result of improper scaling of vehicular responses to control inputs, inadequate sampling of manual control input rates for use in dynamics computations, insufficient update rates for operator feedback systems, and improper quantification of variables' amplitudes during high-speed digital-to-analog and analog-to-digital conversions, among others. In the latter case, inadequate resolution can cause "jumping" in either input or output variables, which are continuous in the vehicle itself.

Control Loading Factors

Damping. Puig (1984) reported the occurrence of PIOs in three simulators of very different designs. The exact cause of these and other inappropriate PIOs in simulators is not known but could be due to a variety of factors such as the aforementioned time delays, control resistance forces, motion system problems, and lack of sufficient pilot training. One design factor which appears to be particularly influential to PIO is control damping. Underdamped systems are more likely to induce control oscillations because the pilot has a tendency to overcontrol the system in an effort to attain a stable attitude. Therefore, the control damping factor may be pertinent to simulator sickness in that if improperly tuned, it can result in continual flight path overshoot and oscillation.

Other control factors. Other control design factors may influence simulator fidelity, control stability and, perhaps to a lesser degree, simulator-induced stress and discomfort. Such factors include elastic resistance (spring-loading), force breakout (pre-load), stiction, sliding friction, viscous friction, excursion limits, velocity limits, control inertia, control deadspace, and control backlash, some of which are discussed in detail in Puig (1984). Each of these factors has direct bearing on the level of proprioceptive correspondence between the control "feel" in the simulator and in the actual system, and therefore may be a source of cue conflict if their fidelity is low and expected feedback is absent or incorrect. For instance, in many high-performance aircraft, control loading increases with g and the pilot learns to associate (and anticipate) the loading with acceleration effects. If similar g-producing maneuvers are presented in the simulator, control loading should mimic that of the actual aircraft so that the pilot will receive the same acceleration cue through the control stick.

Motion System Factors

Motion/no motion. As has been demonstrated in several studies, proper design of certain aspects of the motion cuing systems is quite critical to the avoidance of simulator sickness. Such design aspects include the axes and types of motions included (e.g., Casali and Wierwille, 1980) and the acceleration and position scaling and washout algorithms used (e.g., Puig, 1984; Sinacori, 1967). The question of motion versus no-motion is not so clear-cut, as the addition (and proper tuning) of motion bases to some simulators has greatly reduced the sickness problem (e.g., V/STOL simulator--Sinacori, 1967), while in other devices the motion systems do not seem to alleviate (or in some cases contribute to) discomfort and may be deactivated due to their ineffectiveness in aiding perceived fidelity (e.g., Hall and Parker, 1967; SAAC simulator--Seevers and Makinney, 1979.) Furthermore, it is unlikely that the addition of a good motion base can remedy sickness in a simulator in which the visual scene has dynamic spatial distortions and response infidelities which are sufficiently provocative by themselves.

Illusory motion techniques. Given the limitations of laboratory excursion envelopes, electrohydraulic positioning systems, and the simple fact that the simulator must be "tied to the ground," unlike the aircraft or actual car, it is clear that the best that can be hoped for from a motion system is that it conveys the illusion of being moved, accelerated, etc., as if one were in the actual vehicle. Of course, in the actual vehicle, movements are complete and actually experienced as they exist; in the simulator, movements are attenuated and the hope is that they are not perceived as they actually exist in the simulator, but instead are experienced as the real motion they mimic. The success of the motion cuing system, and to some degree its influence on simulator sickness, is largely dependent upon whether or not the subject is actually fooled, by the vestibular/kinesthetic cues combined with coordinated and sustained visual motion cues, into thinking that he or she has actually completed a full maneuver over hundreds of feet. Basically, this illusion is usually attempted in a simulator motion system by providing a scaled onset motion cue corresponding to a given acceleration cue from the computational dynamics and then tapering this cue off over time, or "washing it out," while sustaining the visual motion on the display. Hopefully, if the desired acceleration would be sustained in the corresponding actual aircraft or automobile for the same maneuver, the visual motion cues in the simulator will compel the pilot or driver to believe that the maneuver is still taking place even though the motion base has fully washed-out and eventually returned to a "null" position for the next maneuver. Of course, the movement rate and excursion that is available for the next maneuver may vary with respect to the instantaneous position of the motion base. For instance, if an aircraft simulator has just provided a 30 degree roll cue and the pilot immediately initiates a second input requiring 30 more degrees of roll, the motion base is likely not capable of providing the same level of cue for the second input as if the base were at wings-level position.

For the motion platform and its associated drive logic, the proper design of such factors as acceleration cuing onset rates, washout rates, nulling or resetting rates and logic, magnitude scaling, center of gravity positioning, etc., is likely quite critical to the avoidance of operator discomfort. For example, research by Kay, Odneal, and Sinacori (1978) demonstrated that with rapid motion washouts, with a break frequency of 1.0 rad/sec, pilots reported nausea and vertigo problems. In his V/STOL simulator research, Sinacori (1967) found that the addition of a pitch, roll, yaw motion base greatly alleviated sickness problems but only when a washout time constant of greater than two to three seconds was used. When short time constants of one second were used, inappropriate PIOs and nausea were reported. Sinacori and others also found that spurious forces, which can result from cross-coupling among motion axes or from certain motion logic, such as using tilt to represent linear accelerations (Casali and Wierwille, 1980), can be disorienting.

Anomalous cues. Motion bases may, sometimes out of necessity of design, also provide movement and positional cues which are anomalous with respect to the actual aircraft in addition to their "true" cues. As noted by Puig (1984), both types of cues must be considered, both separately and interactively, in an investigation of simulator sickness. One simple example exists with the roll axis behavior of some six degree-of-freedom synergistic motion bases in aircraft simulators. In a banked turn, the actual aircraft will roll and bank and the aircrew will feel the reactive effects of an acceleration vector plus a rolling sensation when their heads are tilted with respect to the gravity vector. In the simulator, the cockpit will also roll, providing a tilt sensation, and the hydraulic actuators will give an acceleration onset cue. If the banked turn is sustained, the cockpit of the simulator will slowly return to a level (horizontal) position in the roll axis while the visual scene and attitude gyro remain tilted, corresponding to the aircraft's wing-low attitude. The fact that the cockpit levels out in the simulator, but not in the aircraft, during the sustained banked turn constitutes a false roll position cue of sorts that may create conflict with the visual cues. Furthermore, when the simulator pilot pulls out of the bank to level off, the cockpit rolls from level to the opposite direction (from the assumed roll attitude) and then returns once again to level, to complete the maneuver. The actual aircraft, of course, simply returns to level unless the pilot overshoots. Again, in the simulator, the position of the vestibular organs with respect to the gravity vector may not correlate with that of the actual aircraft.

This simple example is not presented to say that this approach is wrong; on the contrary, it may be the best feasible approach for creating an illusion of turning and banking given available simulator technology. However, it does illustrate the problems inherent in depicting real-world motions in a confined simulator area. Other spurious movements potentially contributing to simulator sickness may arise as a result of parasitic motion between axes, hydraulic actuator "bump" and shudder, and inertial effects during sudden accelerations and reversals.

Motion-induced sickness. As previously noted, some movements produced by the simulator's motion base may simply be provocative of motion sickness by themselves. Pilot-induced oscillatory movements may result in discomfort; these may be caused by a variety of control loading and lag design problems discussed earlier. Furthermore, the occurrence of simulator motion-base resonant frequencies in the problematic range of 0.2 to 0.4 Hz (O'Hanlon and McCauley, 1974) may induce motion sickness, manifested as simulator sickness, as postulated by Frank et al. (1983) and investigated in the SAAC simulator (Hartman and Hatsell, 1976). Therefore, simulators suspected to exhibit high motion energy in this bandwidth range should be power spectral analyzed, using accelerometer data if possible, and adjusted if necessary.

Complementary motion cuing devices. Such devices as g-suits, g-seats, helmet loaders, control loaders, and g-dependent visual scene dimming (simulating a tunnel vision effect), are sometimes included in flight simulators to enhance the illusion of motion effects. The role of these devices in sickness provocation is unknown, but the potential does exist. For instance, the g-suit constricts around the simulator pilot's body when high acceleration maneuvers are simulated; however, there is negligible, if any, actual g-force simulated. Since the typical, in-flight g-effects on the cardiovascular system are not present in the simulator, the g-suit may actually influence blood flow undesirably if its inflation/deflation rate and phase are not properly scaled.

Also, the g-seat device provides limited kinesthetic and somesthetic g-related cues by hydraulic or pneumatic inflation/deflation of cockpit seat pads. In some simulators, these devices may be used in lieu of a vestibular-cuing motion base (e.g., Navy 2E6 Air Combat Maneuvering simulator). However, their excursions and response rates (especially those of the pneumatic seats) are quite limited and their intent is not to provide true inertial cuing. Furthermore, inflation/deflation of the seat pads may cause off-axis viewing of cockpit displays, because the pilot's head position is changed. With this occurrence, visual distortion may occur, heightening the chance of pilot discomfort.

Visual System Factors

Display type. A variety of visual display characteristics are believed to contribute to inducement of simulator sickness. Common modern display systems include point-light source through transparency projection, model board objective with closed-circuit TV, and infinity optics or projection computer-generated imagery (CGI). No systematic study has been performed to determine the effects of each type on simulator sickness, and such a study would be difficult to perform due to the plethora of within-display type variables. However, from the incidental data it appears that simulators with the CGI and point-light source systems are most problematic, with less frequent occurrence in model board devices (McCauley, 1984). Care must be exercised in drawing any conclusions from this observation due to inherent confounding with simulator idiosyncracies.

A number of older simulators utilized motion picture-type displays, on which a roadway or sky-earth scene was presented in front of the subject using a cine-projector and projection screen. Many of these devices were known to induce severe simulator sickness (e.g., Beinke and Williams, 1968; Testa, 1969), particularly those with wide displays such as concave-screen cinerama and cinemascope systems. Also, because the devices utilized display sequences which were actually filmed from a moving vehicle, detail in the scene was usually very high. Perhaps the combination of enriched scene detail and wide field-of-view displayed in two-dimensional perspective contributed to the high incidence of problems accompanying the use of these devices. Furthermore, due to the limited pan angle of the movie projector in relation to the driver's or pilot's point of regard envelope, dynamic distortions were often evident in the visual presentation, particularly during large yaw excursions.

Distortions. A number of spatial and temporal distortions which can occur in simulator displays have been suggested as contributors to simulator sickness. Distortions which are elastic, and therefore not easily adapted to, may be particularly provocative. Exemplary of these are optometric, spatial distortion problems which may vary with operator head position, and temporal problems such as display flicker, image smearing (e.g., resulting from phosphor persistence which is overly long with respect to update rate), and image jitter. Off-axis viewing and parallax may be problematic for crew members not at the display design eye position (e.g., 2F87F simulator--Kennedy, 1981). And as noted by Puig (1984), display luminance level may contribute indirectly to perceived distortion, as with low luminance levels there will be increased spherical aberration due to dilation of the pupil. Other anomalies may include image swimming (inappropriate changes in image resulting from head movements), aliasing, priority (bleed-through), double-imaging and shadowing (ghosting), light leakage at display edges, chrominance and/or image discontinuities between adjacent CRTs or screens, windscreen lensing effects when combined with spherical mirror or fresnel lens infinity optics, and display vibrations which affect visual accommodation.

Most simulators incorporate display optics which are biocular, where both eyes share a single optical axis, rather than binocular, where there are two optical axes (Puig, 1984). In the biocular system, distortions may result from variations in magnification and collimation across the exit pupil of the display, causing difficulties in fusion of the image and potentially influencing simulator sickness (Puig, 1984). Furthermore, numerous anecdotes have alluded to the fact that in some visual display systems, there exist problems with the intended presentation of the scene from an optical infinity perspective. That is, the observer-to-screen distance may not be long enough that the eyes truly accommodate at infinity, so that objects at infinity in the real world would not appear as such in the simulator. Furthermore, in some CRT infinity optics (reflective or refractive) displays, visual cues confirming that the display is really only a few feet away are discernible from the edges of the CRT, beamsplitter hardware, etc. These cues are in direct conflict with the image on the display which is intended to be perceived as if it were at optical infinity.

Field-of-view/scene detail. Another variable which appears critical is visual field-of-view, measured by the horizontal (and vertical) angles subtended at the operator's eyes by the display edges. (e.g., Kennedy, Frank, and McCauley, 1983; Money, 1980; Puig, 1984). Wide field-of-view devices, such as the CGI SAAC and the point-light source 2E6 ACM device, are known to induce discomfort. Perhaps one reason for the field-of-view effect is that the widescreen presentation provides the opportunity for more stimulation of the peripheral retinal receptors of the ambient visual system, which have been shown to be more important in determining spatial orientation and movement than the central retinal receptors (Leibowitz, Post, Brandt, and Dichdans, 1982). Also for this reason, it appears plausible that field-of-view interacts with scene detail and scene complexity in its influence. The higher the scene detail, particularly that presented to the operator's ambient visual system, the greater the stimulation evidencing movement and vection and the greater the likelihood of a conflict with attenuated (or absent) vestibular cues in the simulator (McCauley, 1984). This notion is supported by the high incidence of sickness in wide-screen CGI simulators, such as the SAAC, in which considerable detail, ground growth, and progression cues are available and high resolution of detail is possible, in contrast to the lower reported incidence of sickness in wide-screen point-light source display devices, such as the 2E6 ACM simulator, in which display content is, by comparison, quite simple. Miller and Goodson (1960) reported similar evidence that sickness was more pronounced when low-altitude VFR scenarios were used, as compared to impoverished high-altitude VFR scenarios. Furthermore, night-only simulators, such as the Navy A6 attack aircraft simulator, typically exhibit little or no sickness problems (Puig, 1984).

Dynamic imaging problems. A number of problems emanating from the process of "writing" video display information across a screen face (e.g., as in a CGI raster-scan system) have been mentioned as having potential impact on simulator sickness. For instance, in 2:1 interlaced raster-scan systems, double-imaging of displayed moving objects is common when computer video image information is sampled at rates different (slower) than those of display refresh, which is typically 60 Hz (McCauley, 1984). Also, there may be subthreshold conflicts created by video systems in which beam scan is in different directions on adjacent displays, such as between adjacent cockpit windows in the Air Force SAAC trainer. Other temporal problems may include display flicker (e.g., due to too slow a repetition rate and/or persistence of phosphorescence), image smearing (e.g., due to too lengthy a phosphorescence persistence with respect to repetition rate), and image jittering due to power supply and other unwanted signal fluctuations. Some CGI-display simulators exhibit priority (bleed-through of background objects), shadowing (ghosting), image swimming (jerkiness of image during head movements), and image chrominance and displacement discontinuities between adjacent CRTs or projection screens. The effects of each of these dynamic display problems on spatial disorientation, illusory motion perception, and simulator sickness is largely unknown. However, because some of the problems result from lack of proper maintenance, and from software and video memory anomalies, their presence is fairly common and must be taken into account.

Cockpit Environment Factors

Several other factors pertinent to design of the cockpit or driver's cab of the simulator may influence discomfort. First, the auditory environment should be considered, especially because localization and bearing of aural cues may be used by the simulator operator as indicants of aircraft behavior (e.g., sideslip, stall, velocity, ground effects). If these parameters of sound are not accurate from a psychological fidelity standpoint, the operator may sense inappropriate sound direction, contributing to disorientation.

Temperature regulation and humidity control are other factors which may influence simulator sickness. Extremes in either may compound and accelerate any uneasiness the operator may experience. In this author's experience, many instructors for military simulator training programs indicate that trainees typically ask that cockpit temperature be kept "lower than normal," possibly as a result of the stress induced by the training mission. Furthermore, the displays, computational systems, lighting systems, etc. all radiate heat which must be dissipated from the cockpit environment.

Finally, proper air flow, exchange, and mixing is critical within an enclosed simulator cab. Simulator cabs typically have a number of areas, such as between windscreen lower edge and dash panel, that can trap air and inhibit its mixture with fresh air. If proper airflow is not provided throughout the cockpit, stagnation of breathing air and pocketing of carbon dioxide can occur, potentially heightening operator discomfort.

Interactive Effects

From the preceeding overview of simulator design characteristics with potential for influencing simulator sickness, it appears that the etiology of the problem is quite likely polygenic. Furthermore, there is evidence that many potential factors interact with each other in their effect, sometimes with one influence compounding the strength of another. For instance, a wide field-of-view in the simulator visual system has long been thought to be a provocative stimulus, but its influence is most certainly dependent on the level of detail inherent throughout the scene, the visually-implied movement of display content, optometric and geometric distortion of the scene, and so forth. It can be hypothesized that there exists a range of "threshold" values for certain critical variables, which, if exceeded, may result in a high probability of sickness in operators. When two or more critical variables are combined, such as visual horizontal field-of-view and level of moving scene detail, the threshold values for each may in effect be lowered due to the interaction. For example, an impoverished, but very wide field-of-view display may not induce discomfort whereas a narrow field-of-view display may be quite provocative given enough scene detail conveying progression and vection effects. The possibility for second and higher-order interactive effects exist for within-modality variables, such as for various visual display factors, as well as for between-modality variables, such as the combination of physical motion cue scaling with visually-presented motion scaling.

Due to the large number of simulator design characteristics and also the fact that they are intended to work together to create the illusion of flying or driving, the examination of "main effects" alone may not provide a full explanation of the cause of simulator sickness. This dictates that laboratory investigations of design characteristics address factorial combinations of those variables with potential for interaction and strict control of other variables. On the other hand, the potential for interaction among variables can lead to factorial designs of unwieldy size, so the use of efficient experimental data collection strategies, such as central-composite designs and response surface methodologies, is prudent. In any case, it appears that the simulator sickness etiology is as yet not clearly understood largely because of the interacting effects which can produce uneasiness for specific combinations of independent variables.

PROCEDURAL COUNTERMEASURES

As noted throughout the literature review, several procedures involved in simulator use are thought to influence the incidence of sickness. Some procedures may be valuable training tools and may not be feasible to eliminate, while others are simply undesirable practices which warrant elimination. The effect of some of these procedures may be ameliorated by utilizing the following countermeasure techniques which do not require hardware retrofit of the simulator. The reader is also referred to Frank et al. (1983), McCauley (1984), and Money (1980) for further recommendations.

Situational freeze. Used in many training simulators, this feature involves sudden stop-action of the visual scene and/or the motion base to allow for an instructor's message or to return to a previous flight segment. Freeze can be disorienting, especially if the attitude at the instant of freeze is "off-horizon." Especially in simulations of high-forward thrust aircraft, trainees sometimes report that they feel "shot from a cannon" upon freeze. Also, extreme difficulty in climbing out of the cockpit with the visual scene frozen in non-wings level attitude has been reported by numerous aircrew. Situation freeze is a valuable instructional tool, however, its use should be judicious, off-horizon attitudes should be avoided, and perhaps aircrew should be prompted as to its imminence.

Situational reset. The reset or slewing feature involves rapidly jumping ahead or backward in time to a new flight scenario or previous portion of a current mission. Like freeze, its use is usually limited to training devices, in which the aircrew may view miles of visual information streaming by in compressed time, similar to a fast-forward or fast-rewind situation. As it is not beneficial from either a training or simulator sickness standpoint to require the pilot to view the rapid visual slewing, some instructors simply require the pilot to close the eyes or hold the head down during slewing. In other simulators, display blanking may be used during reset.

<u>Scene blanking on entry/exit</u>. To avoid possible disorientation effects, it is suggested that the simulator's visual scene be turned off prior to boarding and disembarking the simulator.

<u>Exposure duration/intensity</u>. The effects of different mission durations and intensities on discomfort have not been systematically evaluated. However, there is some anecdotal evidence to suggest that operator susceptibility to sickness may be decreased by exposing the operator to increasing mission lengths and intensities in incremental fashion.

<u>Maneuvering effects</u>. Depending on the training or research objectives, it may be infeasible to inhibit the use of certain simulated flight or driving maneuvers. Money (1980) suggested that certain maneuvers may be particularly provocative, such as turning during taxi, sudden and rapid altitude and speed changes, and sustained flight in high turbulence. Hover and low-altitude scenarios have been particularly problematic in helicopter simulators, while rapid driving through tight curvature and sudden changes in grade has been provocative in automobile simulators. Such situations should probably be used in moderation, if possible. Those maneuvers which elicit considerable and sometimes atypical head movement also may be especially provocative.

<u>Motion resonant frequency</u>. In motion-base devices, true motion sickness may result from exposure to vertical acceleratory energy in the bandwidth range of 0.2 to 0.4 Hz. If considerable energy in this range is suspected, spectral analysis and if dictated, subsequent motion-base tuning may help ameliorate the problem.

Pre-simulator briefing. Some trainees or research subjects may benefit from a briefing with the instructor or experimenter prior to their initial simulator ride, regarding what to expect in the simulator and how to deal with any problems that they may experience. Some simulators may have an aura of sickness about them, fostered through anecdotes and gossip of former users. Briefings may prove essential with these "notorious" devices, to eliminate any pre-bias a new trainee may have developed through talking with others. If briefings are not used, by simple power of suggestion, naive trainees may be predisposed to sickness in a particular simulator because they feel that the sickness is a normal reaction, perhaps even one expected of them.

Susceptibility tests. There is some empirical evidence that such test instruments as the previously-discussed Pensacola Motion Sickness Questionnaire (e.g., Kennedy, Frank et al., 1984) and certain perceptual style metrics (e.g., Barrett and Thornton, 1968b) may be used to predict those individuals who are particularly susceptible to simulator sickness. This would primarily be useful for screening research subjects who are likely to experience sickness.

Individual health. It is generally recommended that individuals who are experiencing the effects of such maladies as influenza, ear infection, stomach virus, hangover, decompression sickness, etc. not be placed in simulators, as their susceptibility to simulator sickness is probably heightened.

Anti-motion sickness drugs. Several authors (e.g., Money, 1980) have suggested that medication may aid in reducing the symptoms of simulator sickness for some individuals and may be appropriate in some situations. Of course, the side effects of such current drugs, particularly those which degrade motor control and attentional skills, probably preclude their use in flight training applications.

<u>Simulator maintenance</u>. The sickness-inducing simulator which has strayed from its optimal calibration state may benefit from a complete calibration check and maintenance procedures. This may target problem areas conducive to simulator sickness, such as control loop lags and delays, control linkage tolerances, display alignment and optical adjustment, display chrominance adjustment, display flicker, and ventilation system adjustment among others.

Most of the aforementioned countermeasures should be considered as only interim strategies to reduce the incidence of simulator sickness. Further research regarding both simulator design characteristics and usage procedures is imminently needed to alleviate the sickness problem in future simulators. And this research data may also dictate hardware retrofit, not just procedural countermeasures, in existing simulators. Given the vast application potential of vehicular simulators and the large investments they entail, it is incumbent upon simulator users, designers, and researchers to reckon with, and solve, the simulator sickness problem.

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APPENDIX

Tabular Overview of Simulator Sickness Documentation and Corresponding Flight and Driving Simulator Characteristics

(adapted from Casali and Frank, 1986)

Overview Table Explanation

In this Appendix, a brief overview of the literature citing specific instances of simulator sickness is presented. For ease of reference, the overview is presented in tabular format and is intended to be used to augment the literature review in the body of this report. All available references having direct mention of simulator sickness occurrences among flight trainees or research subjects were obtained and reviewed. Most of the literature on simulator sickness consists of either formal documentation or anecdotal mention of the subject or trainee discomfort arising from the use of a particular simulator. Usually these reports of sickness are mentioned in the context of their hindrance to the objectives of a simulator evaluation, training, or research effort and are not the focus of empirical investigation in the document. Some reports are very scant in their documentation of the sickness problem while others offer much insight into the potential causes of sickness specific to the simulator and mention potential countermeasures to alleviate the problem. Other reports detail controlled research efforts aimed directly at investigation of the etiology of the simulator sickness problem. In all cases, the reports are reviewed herein to the fullest extent possible with respect to those aspects pertinent to simulator sickness.

The overview tables are organized as follows. Table 1 presents information regarding driving simulators which are known to elicit simulator sickness or have been used in studies of simulator sickness. Whenever possible, aspects of the simulator visual display, motion system, operator cockpit, auditory system, operating procedures, intended applications, and corresponding actual vehicle are included in Table 1. Table 1 is intended to be paired with Table 2 which represents an attempt to annotate pertinent information from reports of driving simulation sickness in a manner facilitating comparison across studies. Blanks in the table indicate that the information was either not evaluated or not reported in the study. Significant effects refer only to statistically-significant findings. In like fashion, Table 3 and Table 4 present analogous information for flight simulators, for which greater documentation of simulator sickness is available.

Table 5 presents the relative incidence of simulator sickness in 13 additional simulators which were not amenable to the format of Tales 2 and 4. (Engineering details of each of these simulators are provided in Tables 1 and 3.) The incidence rates reported by Kennedy, Dutton, Ricard, and Frank (1984) for the flight simulators represent preliminary results of a comprehensive field study by the Naval Training Equipment Center. Several human performance and engineering measures have been and are currently being collected; these have yet to be fully analyzed.

Table 1. Driving simulator characteristics.[1]

Sim. Designation	Goodyear Aerospace I	Goodyear Aerospace II	UCLA I	General Motors Technical Center
Actual Vehicle	automobile	automobile	automobile	automobile
Type Vehicle	full-size sedan	full-size sedan	full-size sedan	general
Application	research	research	research & driver rehab.	research
Visual System				
Type	CCTV projection	CCTV monitor	motion picture	motion picture
Image Source	model board	model board	film	film
Medium	spherical screen	CRT	spherical screen	spherical screen
Infinity ∞ cuing	viewing distance	reflective ∞ optics	viewing distance	reflective optics
Lighting Cond.	daylight	daylight	adj. by film	adj. by film
H/V FOV (deg)[2]	50/39	54/unk.	150/unk	77-50/unk.
Scene Content	road & periphery	road & periphery	film of actual road	film of actual road
Motion System				
Type	fixed-base	fixed-base	fixed-base	cascade
Deg of Freedom[2]	-	-	-	tilt sim. of LN,LT accel.
g-seat/g-suit	-	-	-	-
g-display sim	-	-	-	-
Vibration	-	-	yes	yes
Cockpit Environ.				
Cab type	car body	car body	car body	enclosed custom
No. Crew	driver	driver	driver, passenger	driver
Audio	engine, drivetrain	engine, drivetrain	engine, drivetrain	engine, drivetrain, tire
Operating Proced.				
Part/Whole Task	whole	whole	whole	whole
Typ. Task Length	30 min.	30 min.	unk.	unk.
Freeze Capa.	-	-	-	-
Slew/Reset Capa.	-	-	-	-
Ext. View [illegible]	unk.	unk.	unk.	unk.
Other Characteristics				

[1] as exi[illegible] [illegible]les referenced in Table 2.

[2] H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical ([illegible]).

Table 1. Driving simulator characteristics.[1] (Continued)

Sim. Designation	General Precision Sim-L-Car	North American Rockwell	VPI&SU
Actual Vehicle	automobile	automobile	automobile
Type Vehicle	general	general	adjustable car
Application	research	research	research
Visual System			
Type	point-light proj.	CCTV projection	CGI
Image Source	transparency	model board	hybrid CGI
Medium	flat, rear-projected screen	screen	monochrome CRT
Infinity ∞ cuing	refraction, 6 ft. viewing distance	unk.	refractive ∞ optics
Lighting Cond.	sunset	unk.	dusk, night
H/V FOV (deg)	45/unk.	~ 39/52	~ 48/30
Scene Content	road & objects	road & signs	road & periphery, other vehicles
Motion System			
Type	fixed-base	cascade	cascade
Deg of Freedom[2]	-	V; tilt sim. of LN, LT accel.	R, Y, LN, LT
g-seat/g-suit	-	-	-
g-display dim	-	-	-
Vibration	-	yes	yes
Cockpit Environ.			
Cab type	car components	enclosed custom	open/enclosed custom
No. Crew	driver, passenger	driver	driver
Audio	engine, drivetrain	engine, road noise	engine, drivetrain road noise, tire
Operating Proced.			
Part/Whole Task	whole	whole	whole
Typ. Task Length	10 min.	unk.	20 min.
Freeze Capa.	-	-	-
Slew/Reset Capa.	-	-	-
Ext.View Allowed	unk.	unk.	not by subjects
Other Characteristics			operation in dark room

[1]as existing in studies referenced in Table 2.
[2]H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

Table 2. Driving simulator study summary.

Author(s)	Barrett & Nelson (1965)	Barrett & Nelson (1966)	Barrett & Thornton (1968b)
Simulator Designation	Goodyear Aerospace I	Goodyear Aerospace II	Goodyear Aerospace I & II
Type Report	Laboratory	Laboratory	Laboratory
Intent	simulator evaluation	virtual image display evaluation	perceptual style differences[5]
Simulator Tasks			
Scenario	freeway driving w/stops	freeway driving w/stops	freeway driving w/stops
Duration	30-50 min.[5]	30-50 min.[5]	30-50 min.[6]
Subjects			
Type	male engineering dept. employees	male engineering dept. employees	male engineering dept. employees
Number	25	25	46
Active/Passive	active	active	active
Independent Variables	emergency stop, speed	emergency stop, speed	emergency stop, speed
Dependent Measures[1]	D,S	D,S	D,S,Q
% Incidence Sickness	64	72	
% Leaving Simulator	44	56	50
Signs/Symptoms[2]			
Queasiness			
Sweating	x	x	
Nausea	x	x	
Emesis	x		
Eyestrain		x	
Headache		x	
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			
Disorientation	x		
Visual Dysfunction			
Ataxia			
Dizziness	x	x	
Vertigo			
Aftereffects			
Other	upset stomach faint feelings		Subject rating of discomfort, subject estimate of discomfort duration, No. trials subject able to stay in sim., rod & frame test
Habituation Effects[3]			
Experience Effects[4]			
Instructor/Student Effects			
Significant Effects			Extremely field independent, more susceptible

[1]How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.
[2]A number indicates % incidence; x-occurrence reported, but not by %.
[3]Lessens with exposure.
[4]More experienced real-world vehicle operators more susceptible.
[5]This was a post-hoc analysis of the effects of field independence/dependence on the Barrett and Nelson (1965, 1966) data.
[6]Estimated from Barrett and Nelson (1965, 1966).

Table 2. Driving simulator study summary. (Continued)

Author(s)	Testa (1969)	Reason & Diaz (1971)	Casali & Wierwille (1980)
Simulator Designation	UCLA I	Sim-L-Car	VPI&SU
Type Report	Laboratory	Laboratory	Laboratory
Intent	simulator sickness	simulator sickness	simulator sickness
Simulator Tasks			
Scenario	two-lane winding mountain road	winding perimeter road	freeway driving
Duration		10 min.	20 min.
Subjects			
Type	male college students	students/technicians	students
Number	40	15 male/16 female	64
Active/Passive	active	passive	active
Independent Variables	perceptual style instructional set	restricted vision sex driving experience	lateral accel. cuing delayed dynamic feedback simulator enclosure perceptual style
Dependent Measures[1]	R,Q	Q	Q,R
% Incidence Sickness	100	90	
% Leaving Simulator		1 case	
Signs/Symptoms[2]			
Queasiness			
Sweating	x	29	
Nausea		42	
Emesis			
Eyestrain			
Headache		45	
Pallor		29	x
Respiration Changes	x		x
Skin Resistance Changes			x
Heart Rate Changes			
Fatigue/Drowsiness		3	
Disorientation			
Visual Dysfunction			
Ataxia			
Dizziness		71	
Vertigo			
Aftereffects			
Other	galvanic skin response rod & frame test embedded figures test instructional set	Bodily warmth-48% stomach awareness-42% increased salivation-19% drymouth-6%	pulse rate arithmetic proficiency yaw standard deviation steering reversals
Habituation Effects[3]			
Experience Effects[4]		x	
Instructor/Student Effects			
Significant Effects	sweating, respiration, perceptual style instructional set	females more susceptible experience	pallor, skin resistance, respiration rate, yaw deviation, no.steering reversals

[1]How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.
[2]A number indicates % incidence; x-occurrence reported, but not by %.
[3]Lessens with exposure.
[4]More experienced real-world vehicle operators more susceptible.
[5]This was a post-hoc analysis of the effects of field independence/dependence on the Barrett and Nelson (1965, 1966) data.
[6]Estimated from Barrett and Nelson (1965, 1966).

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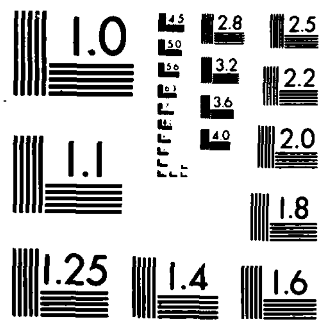

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Table 3. Flight simulator characteristics.[1]

Sim. Designation	2-FH-2	V/STOL	2F87F I	2F87F II
Actual Vehicle	Bell HTL-4	General V/STOL	P-3C turboprop	P-3C turboprop
Type Vehicle	helicopter	jet-lift	patrol	patrol
Application	hover training	research	training	training
Visual System				
Type	point-light proj.	point-light proj.	CCTV monitor Rediffusion Duoview	CGI MDEC[4] Vital IV
Image Source	transparency	transparency	model board	digital CGI
Medium	curved screen	spherical screen	CRTs	calligraphic CRTs
Infinity ∞ cuing	refraction, 6-12 ft. viewing distance	reflection, viewing distance	reflective ∞ optics	reflective ∞ optics
Lighting Cond.	dim, daylight	daylight	day, dusk, night	dusk, night
H/V FOV (deg)[2]	260/75	100/30	48/36[3]	48/36[3]
Scene Content	sky, earth	sky, earth, objects	sky, earth	sky, earth
Motion System				
Type	fixed-base	unk.	synergistic	synergistic
Deg of Freedom[2]	-	P, R, Y	all 6	all 6
g-seat/g-suit	-	-	-	-
g-display dim	-	-	-	-
Vibration	yes	unk.	-	-
Cockpit Environ.				
Cab type	open	unk.	enclosed, A/C cab	enclosed, A/C cab
No. Crew	2	1	3	3
Audio	engine	unk.	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	whole flight	unk.	takeoff & land	takeoff & land
Typ. Task Length	30 min.	unk.	4 hr.	4 hr.
Freeze Capa.	yes	yes	unk.	unk.
Slew/Reset Capa.	yes	-	unk.	unk.
Ext.View Allowed	unk.	unk.	unk.	unk.
Other Characteristics	control lag noted	orig. fixed-base, motion added		flight engr. had off-axis display view--caused sickness

[1]as existing in studies referenced in Table 4.
[2]H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[3]one window FOV; monochrome display added for flight engr. in Brunswick, ME, device (no. II).
[4]McDonnell-Douglas Electronics Corporation.

Table 3. Flight simulator characteristics.[1] (Continued)

Sim. Designation	(2 cockpits) SAAC	CP 140 FDS	2E6 ACM (2 cockpits)	2F112
Actual Vehicle	F-4 jet	Aurora turboprop (P-3C)	F-14/F-4 jet	F-14 jet
Type Vehicle	fighter	patrol	fighter	fighter
Application	air-air combat training	training, limited research	air-air combat training	air-air combat & misc. training
Visual System				
Type	CGI mosaic[3]	CGI	point-light proj.[3] MDEC	point-light proj.[4]
Image Source	digital CGI	digital CGI	2 transparency spheres	2 transparency spheres
Medium	8 monochrome raster CRTs	2 CRTs	40 ft. dia. dome	40 ft. dia. dome
Infinity ∞ cuing	reflective ∞ optics	unk.	20 ft. viewing distance	20 ft. viewing distance
Lighting Cond.	unk.	dusk, night	day, dusk, night	day, dusk, night
H/V FOV (deg)[2]	~ 296/180	unk.	~ 350/280	~ 350/280
Scene Content	sky, earth, A/C	sky, earth, objects	sky, earth, A/C	sky, earth, objects, carrier
Motion System				
Type	synergistic	synergistic	fixed-base	fixed-base
Deg of Freedom[2]	all 6	all 6	-	-
g-seat/g-suit	both	-	both	both
g-display dim	yes	-	yes	yes
Vibration	-	-	control stick vib.	control stick vib.
Cockpit Environ.				
Cab type	actual cockpits w/ canopies	enclosed	actual cockpit w/ canopies	actual cockpit w/ canopy
No. Crew	1 ea. cockpit	3	2 ea. cockpit	2
Audio	yes, multiple	yes, multiple	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	in-air combat	whole flight	in-air combat	whole flight
Typ. Task Length	45-60 min.	30 min.-2 hr.	45 min.-1 hr.	1-1.5 hr.
Freeze Capa.	yes	yes	yes	yes
Slew/Reset Capa.	yes	yes	yes	yes
Ext.View Allowed	unk.	unk.	no	no
Other Characteristics	0.2-0.4 Hz motion spectrum component apparent		gantry handrails in view of cockpit	

[1]as existing in studies referenced in Table 4.
[2]H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[3]CCTV camera model target projectors.
[4]CCTV camera model target projectors and CGI carrier for landing via MDEC Vital IV.

Table 3. Flight simulator characteristics.[1] (Continued)

Sim. Designation	2F106	2F64C	2F110	2F117
Actual Vehicle	SH-2F	SH-3	E-2C turboprop	CH-46E
Type Vehicle	helicopter	helicopter	AEW/tactical	helicopter
Application	training	training	training	training
Visual System				
Type	CGI MDEC Vital III	CGI MDEC Vital IV	CGI Rediffusion Noroview SP1	CGI Rediffusion CT5
Image Source	digital CGI	digital CGI	digital CGI	digital CGI
Medium	calligraphic CRTs	calligraphic CRTs	calligraphic CRTs	raster CRTs
Infinity ∞ cuing	reflective ∞ optics	reflective ∞ optics	reflective ∞ optics	reflective ∞ optics
Lighting Cond.	night	dusk, night	dusk, night	day, dusk, night
H/V FOV (deg)	~ 144/32	130/30 & chin window	~ 139/35	200/50 & chin window
Scene Content	sky, earth, ships, objects	sky, earth, ships, objects	sky, earth, carrier, objects	sky, earth, ships, objects
Motion System				
Type	synergistic	synergistic	synergistic	synergistic
Deg of Freedom[2]	all 6	all 6	all 6	all 6
g-seat/g-suit	-	-	-	-
g-display dim	-	-	-	-
Vibration	yes, multiple	yes	yes	yes
Cockpit Environ.				
Cab type	enclosed helo. cab	enclosed helo. cab	enclosed A/C cab	enclosed helo. cab
No. Crew	2	2	2	2
Audio	yes, multiple	yes, multiple	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	whole flight	whole flight	whole flight	whole flight
Typ. Task Length	1.5 hr.	unk.	2-2.5 hr.	1.5-2 hr.
Freeze Capa.	yes	yes	yes	yes
Slew/Reset Capa.	-	yes	yes	yes[3]
Ext.View Allowed	yes	unk.	yes	yes
Other Characteristics				

[1]as existing in studies referenced in Table 4.
[2]H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[3]crew instructed not to view display during reset.

Table 3. Flight simulator characteristics.[1] (Continued)

Sim. Designation	2F121	2E7 ACTT (2 cockpits)	2F132
Actual Vehicle	CH-53D	F-18 jet	F-18 jet
Type Vehicle	helicopter	fighter	fighter
Application	training	air-air combat & tactics	training
Visual System			
Type	CGI Rediffusion CT5	CGI[4] IMI generator	CGI MDEC Vital IV
Image Source	digital CGI	CGI	digital CGI
Medium	raster CRTs	raster TV proj. on 35 ft. dia. dome	raster TV proj. onto dome
Infinity ∞ cuing	reflective ∞ optics	viewing distance	viewing distance
Lighting Cond.	day, dusk, night	day, dusk, night	dusk, night
H/V FOV (deg)[2]	200/50 & chin window	~ 360/150	~ 48/32
Scene Content	sky, earth, ships, objects	sky, earth, A/C	sky, earth, carrier objects
Motion System			
Type	synergistic	fixed-base	fixed-base
Deg of Freedom[2]	all 6	-	-
g-seat/g-suit	-	both	both
g-display dim	-	yes	unk.
Vibration	yes	yes	-
Cockpit Environ.			
Cab type	enclosed helo. cab	actual cockpits w/canopies	actual cockpit w/canopy
No. Crew	2	1	1
Audio	yes, multiple	yes, multiple	yes, multiple
Operating Proced.			
Part/Whole Task	whole flight	in-air combat	takeoff & land
Typ. Task Length	1.5-2 hr.	unk.	unk.
Freeze Capa.	yes	yes	yes
Slew/Reset Capa.	yes[3]	unk.	yes
Ext.View Allowed	yes	unk.	-
Other Characteristics			dynamic replay seat buffet carrier takeoff/landing

[1]as existing in studies referenced in Table 4.
[2]H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[3]crew instructed not to view display during reset.
[4]CGI target projection via Rediffusion CT5.

Table 4. Aircraft simulator study summary.

Author(s)	Havron & Butler (1957)	Miller & Goodson (1958, 1960)	Ryan, Scott, & Browning (1978)
Simulator Designation	2-FH-2	2-FH-2	2F87F 1
Type Report	field study	field study	field study
Intent	training effectiveness eval.	simulator sickness	transfer of training
Simulator Tasks			
Scenario	footnote 5	footnote 5	landing
Duration	30 min.	30 min.	4 hrs.
Subjects			
Type	instr./student pilots	instr./student pilots	instr./student pilots
Number	36	10	47
Active/Passive	active	active	active
Independent Variables			motion/no motion
Dependent Measures[1]	Q	Q, I	Q
% Incidence Sickness	78[6]	60 instructor, 12 student	11
% Leaving Simulator			
Signs/Symptoms[2]			
Queasiness			
Sweating	x		
Nausea	x		
Emesis			
Eyestrain			
Headache	x		6
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			
Disorientation			
Visual Dysfunction			
Ataxia			11
Dizziness			
Vertigo	x	x	
Aftereffects	x	x	
Other			
Habituation Effects[3]	x	x	
Experience Effects[4]	x	x	
Instructor/Student Effects	x	x	
Significant Effects			

[1] How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.

[2] A number indicates % incidence; x-occurrence reported, but not by %.

[3] Lessens with exposure.

[4] More experienced real-world vehicle operators more susceptible.

[5] Two scenarios--low level (55') or high level (500') maneuvers.

[6] In addition, 11 instructors were assigned to the simulator, but 7 had to quit because of sickness.

Table 4. Aircraft simulator study summary. (Continued)

Author(s)	Crosby & Kennedy (1982)	Kellogg, Castore, & Coward (1980)	Hartman & Hatsell (1976)
Simulator Designation	2F87F II	SAAC	SAAC
Type Report	field study	field observation	field study
Intent	simulator sickness	simulator sickness	simulator sickness
Simulator Tasks			
Scenario	patrol mission	air combat maneuvering	air combat maneuvering[5]
Duration	4 hrs.	about 60 min.	about 60 min.
Subjects			
Type	flight engineers	pilot	pilot
Number	20 plus	48	100-114
Active/Passive	passive	active	active
Independent Variables	field-of-view		
Dependent Measures[1]	D,Q,I	I	Q,I
% Incidence Sickness	50	88	52
% Leaving Simulator			
Signs/Symptoms[2]			
Queasiness			
Sweating		54	
Nausea		79	14
Emesis			2
Eyestrain			50
Headache			
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			38
Disorientation			52
Visual Dysfunction			
Ataxia	50	60	
Dizziness			
Vertigo			
Aftereffects	x		
Other		spinning sensations-54% maneuver. sensations-25% headache, leans, dizziness or loss of situational awareness-23% vivid involuntary flashbacks-35% vivid dreams, daydreams-35% inverted visu field-10%	
Habituation Effects[3]		x	
Experience Effects[4]			
Instructor/Student Effects			
Significant Effects			

[1]How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.

[2]A number indicates % incidence; x-occurrence reported, but not by %.

[3]Lessens with exposure.

[4]More experienced real-world vehicle operators more susceptible.

[5]Also had a maximum maneuvering scenario.

Table 4. Aircraft simulator study summary. (Continued)

Author(s)	Money (1980)	McGuinness, Bouwman & Forbes (1981)
Simulator Designation	CP 140 FDS	2E6[7]
Type Report	field study	field survey
Intent	simulator sickness	simulator sickness
Simulator Tasks		
Scenario		air combat maneuvering
Duration		30-45 min.
Subjects		
Type	pilots	pilots/navigators
Number	14	66
Active/Passive	active	active/passive
Independent Variables		
Dependent Measures[1]	Q	Q
% Incidence Sickness	43[5]	27
% Leaving Simulator		
Signs/Symptoms[2]		
Queasiness		
Sweating		
Nausea	x[6]	9
Emesis		
Eyestrain		
Headache		7
Pallor		
Respiration Changes		
Skin Resistance Changes		
Heart Rate Changes		
Fatigue/Drowsiness		11
Disorientation		
Visual Dysfunction		8
Ataxia		
Dizziness		17
Vertigo		11
Aftereffects		x
Other		leans-9% discomfort-8% other-9%
Habituation Effects[3]	x	
Experience Effects[4]		x
Instructor/Student Effects		
Significant Effects		

[1]How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.
[2]A number indicates % incidence; x-occurrence reported, but not by %.
[3]Lessens with exposure.
[4]More experienced real-world vehicle operators more susceptible.
[5]Three other individuals experienced symptoms while working, observing, or flying the simulator.
[6]Slight discomfort to mild nausea.
[7]Both F-4 and F-14 cockpits evaluated.

TABLE 5. Simulator sickness incident reports.

Simulator Designation	Vehicle	Active/Passive	Sample Size	Incidence
General Motors Technical Center[1]	generic auto	active	50 plus[2]	2 cases plus[2]
North American Rockwell[3]	generic auto	active	40	3 cases
V/STOL[4]	jet-lift	active	1	1 case
2F112[5]	F-14	active	65	16%
2F106[5]	SH-2F	active	28	13%
2F64C[5,6]	SH-3	active	153	55%
2F110[5]	E-2C	active	75	49%
2F117[5]	CH-146E	active	160	29%
2F87[5]	P-3C	active	55	44%
2F121[5]	CH-53D	active	208	36%
2E-7[5]	F/A-18	active	102	33%
2F132[5]	F/A-18	active	26	23%

[1] Beinke and Williams (1968)

[2] Precise figures not provided

[3] Breda, Kirkpatrick, and Shaffer (1972)

[4] Sinacori (1967)

[5] Kennedy, Dutton, Ricard, and Frank (1984)

[6] Simulator located on east coast

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